THE COST-EFFECTIVENESS OF COMMERCIAL BUILDINGS COMMISSIONING

A Meta-Analysis of Existing Buildings and New Construction in the United States

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An electronic version of this document and data forms are available at
http://eetd.lbl.gov/emills/PUBS/Cx-Costs-Benefits.html

DISCLAIMER

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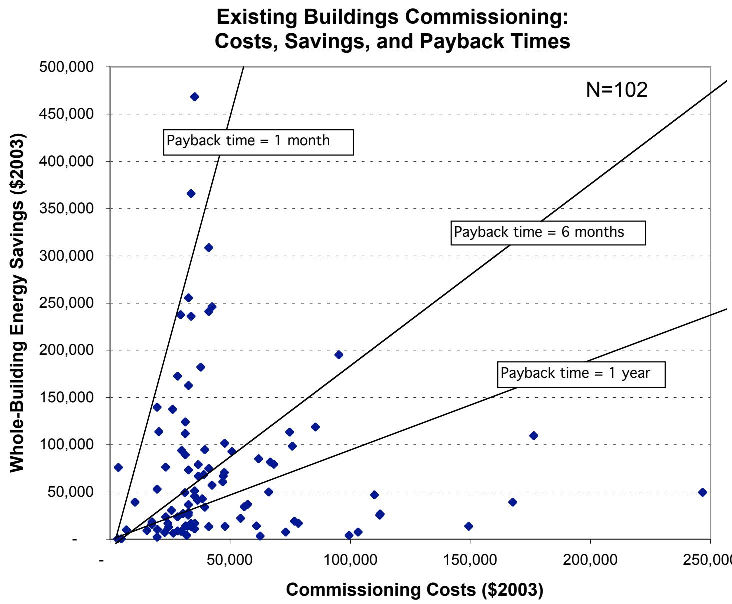
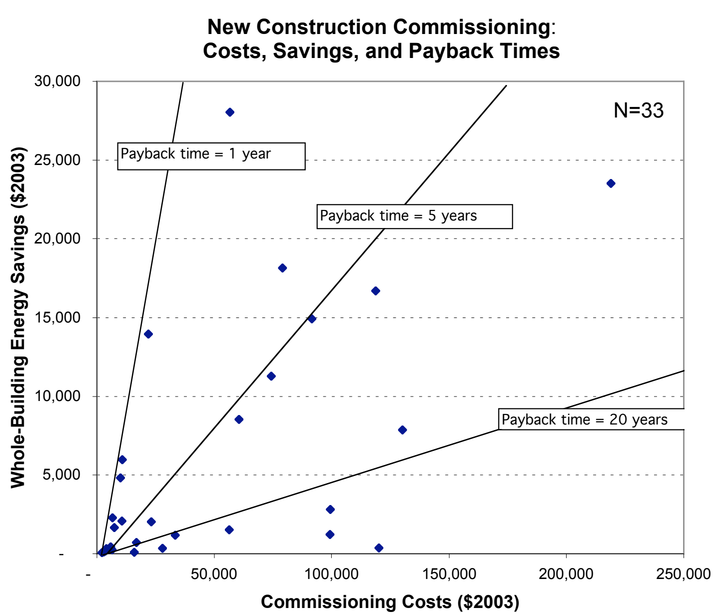
SUMMARY

Building performance problems are pervasive. Deficiencies such as design flaws, construction defects, and malfunctioning equipment have a host of ramifications, ranging from equipment failure, to compromised indoor air quality and comfort, to unnecessarily elevated energy use or under-performance of energy-efficiency strategies. Fortunately, an emerging form of quality assurance—known as building commissioning—can detect and remedy most deficiencies.

Scattered case studies and anecdotal information form the basis of the conventional wisdom among energy-management professionals that commissioning is highly cost-effective. However, given the lack of standardized information on costs and benefits of detecting and correcting deficiencies, it is perhaps of no surprise that the most frequently cited barrier to widespread use of commissioning is decision-makers' uncertainty about its cost-effectiveness.



Designed as a "meta-analysis," this report compiles and synthesizes extensive published and unpublished data from commissioning projects undertaken across the United States over the past two decades, establishing the largest available collection of standardized information on building commissioning experience. We analyze results from 224 buildings across 21 states, representing 30.4 million square feet of commissioned floor area (73 percent in existing buildings and 27 percent in new construction). These projects represent $17 million ($2003) of commissioning investment. The new-construction cohort represents $1.5 billion of total construction costs.



We develop a detailed and uniform methodology for characterizing, analyzing, and synthesizing the results. For existing buildings, we found median commissioning costs of $0.27/ft^2, whole-building energy savings of 15 percent, and payback times of 0.7 years. For new construction, median commissioning costs were $1.00/ft^2 (0.6 percent of total construction costs), yielding a median payback time of 4.8 years (excluding quantified non-energy impacts).

These results are conservative, insofar the scope of commissioning rarely spans all fuels and building systems in which savings may be found, as not all commissioning recommendations are implemented, and significant first-cost and ongoing non-energy benefits are rarely quantified. Examples include reduced change-orders thanks to early detection of problems during design and construction, rather than after the fact, or correcting causes of premature equipment breakdown. Median one-time non-energy benefits were -$0.18/ft^2$-year for existing buildings (10 cases) and -$1.24/ft^2$-year for new construction (22 cases)–comparable to the entire cost of commissioning.

Deeper analysis of the results shows cost-effective outcomes for existing buildings and new construction alike, across a range of building types, sizes and pre-commissioning energy intensities. The most cost-effective results occurred among energy-intensive facilities such as hospitals and laboratories. Energy savings tend to rise with increasing comprehensiveness of commissioning.

The projects identified 3,500 deficiencies (11 per building, 85 projects reporting) among existing buildings and 3,305 (28 per building, 34 projects reporting) among new construction. In both cases, problems with air-distribution systems and correctional measures focusing on operations and control were more pervasive than those with specific pieces of equipment.

There are material differences between our results for existing buildings and new construction. This can be seen in the "bottom-line" results per unit floor area—six-fold greater energy savings and four-fold lower commissioning costs for existing buildings. It should be noted, however, that median payback times are attractive in both cases, especially when non-energy impacts are accounted for. Larger median building floor areas in our existing-buildings sample (151,000 square feet) tended to favor lower costs compared to the new-construction cases (69,500 square feet). New-construction commissioning is more strongly driven by non-energy objectives such as overall building performance, thermal comfort, and indoor air quality whereas existing-building commissioning is more strongly driven by energy savings objectives. The need for commissioning in new construction is indicated by our observation that the number of deficiencies identified in new-construction exceed that for existing buildings by a factor of six.

Some view commissioning as a luxury and "added" cost, yet it is only a barometer of the cost of errors promulgated by other parties involved in the design, construction, or operation of buildings. Commissioning agents are just the "messengers"; they are only revealing and identifying the means to address pre-existing problems.

We find that commissioning is one of the most cost-effective means of improving energy efficiency in commercial buildings. While not a panacea, it can play a major and strategically important role in achieving national energy savings goals—with a cost-effective savings potential of $18 billion per year or more in commercial buildings each year. Commissioning is under-attended in public-interest deployment programs as well as research and development activities. As technologies, controls, and their applications change and/or become more complex in an effort to capture greater energy savings, the risk of under-performance will rise and with it the value of commissioning. Indeed, innovation driven by the desire for increased energy efficiency may itself inadvertently create energy waste if those systems are not designed, implemented, and operated properly. The ultimate impact of energy efficiency research and development portfolios, as well as deployment programs, lies in no small part in the extent to which they are coupled with cost-effective quality assurance.

INTRODUCTION

Goals of this Study

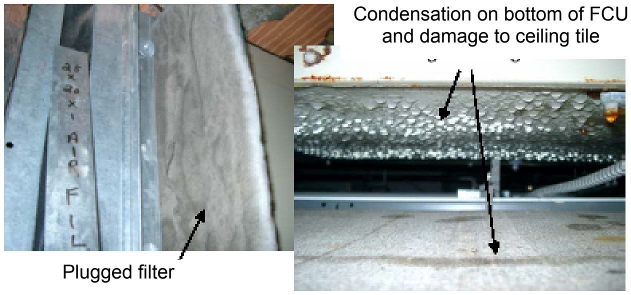
Few buildings perform as intended. Numerous pervasive and chronic performance deficiencies stem from design flaws, construction defects, malfunctioning equipment, and deferred maintenance. These deficiencies—exemplified in the montage of Boxes 1 and 2—have a host of ramifications, ranging from equipment failures to compromised indoor air quality and comfort to unnecessarily elevated energy use. For similar reasons, energy-saving design concepts for new buildings or retrofits for existing ones often fail to deliver predicted savings.

In response to growing awareness of these problems, quality assurance techniques collectively known as commissioning[1] have emerged over the past two decades to address deficiencies in new construction and existing buildings alike. In its highest form, the commissioning process treats the building as a system, and uses inspection and testing to implement measures designed to optimize overall energy and non-energy performance. Energy-oriented commissioning is one of the newest fields within the overall energy management arena, offering greater and more cost-effective energy savings than many traditional "hardware" strategies.

According to an estimate from the late 1990s, less than five percent of buildings are commissioned when built—the majority for non-energy reasons—and less than 0.03 percent of existing buildings are commissioned each year (PECI 1998). Lack of information on costs and benefits is often cited among the top-most reasons that market penetration remains low (PECI 1998; Willems 1999; Altwies and McIntosh 2001; Veltri 2002; SBW and Skumatz 2003; Friedman *et al.* 2004). As suggested by slow market uptake, there remains an acute need to better understand the economics of commissioning. Designed as a "meta-analysis," this report synthesizes existing data from real-world commissioning projects across the United States and over the period 1984 to 2003. By examining a large body of primary data (e.g., commissioning agents' project files) and published reports, we delve more deeply into certain areas—e.g., the structure of commissioning costs and funding—than has been done in past studies. We also analyze reported reasons for commissioning and non-energy impacts, as they are important indicators of benefits and hence integral to any comprehensive cost-benefit analysis (Mills and Rosenfeld 1996). We develop a detailed and uniform methodology and benchmarks for characterizing the results of projects and normalizing the data to facilitate inter-comparisons. The resulting database represents the largest available collection of standardized information on commissioning experience in actual buildings. Our assessment enables building owners and policymakers to make more definitive conclusions about cost-effectiveness and other impacts than has been possible up until now.

[1] The terms "retrocommissioning" and "recommissioning" are commonly applied to existing buildings and "commissioning" to new construction. We use the more literal (and hopefully accessible) terms "existing buildings" or "new construction" to differentiate between the two major branches of commissioning. In this report, instances of the term "commissioning" without these modifiers generally refer to both types collectively, unless the context of usage supports a clear distinction.

Box 1. Common deficiencies with adverse energy ramifications identified during retro-commissioning. Courtesy Martha Hewett, Minnesota Center for Energy & Environment.



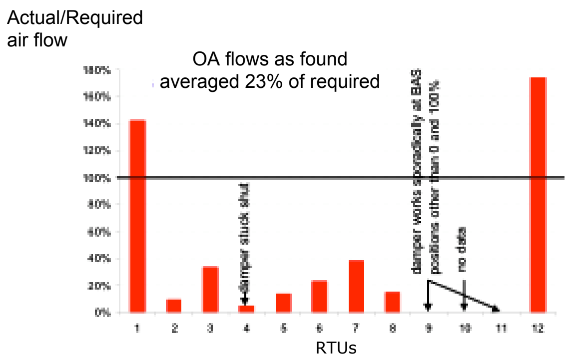
Condensation damage from DX fan coil unit due to plugged filter and low air flow, large high school.

Broken actuator arm on dampter of multizone unit, elementary school.

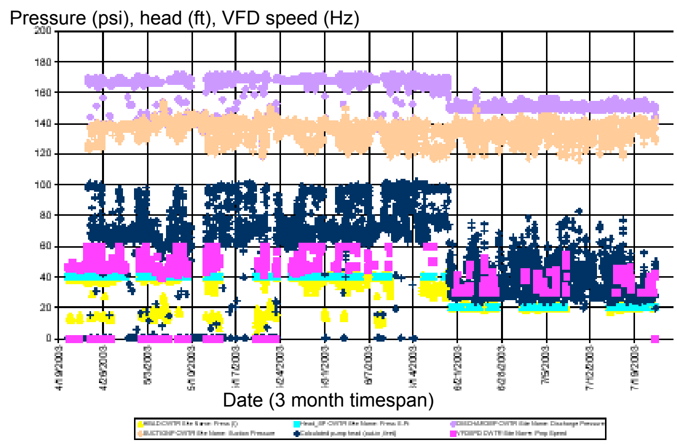
Inadequate cooling and excessive fan power consumption due to poor fit between light troffer diffusers and duct boot provided by a different supplier, allowing up to 25% of flow at diffuser to bypass directly into ceiling plenum. Highrise office tower.

Damage to brick facade of pool building due to lack of specification for (a) sealing of air leakage paths in exterior envelope and (b) balancing to assure negative pressurization of pool area. Large newer middle school.

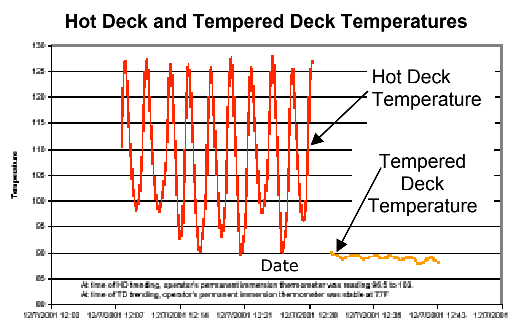
Box 2. Fingerprints of deficiencies identified during retro-commissioning. Building automation systems and associated data-acquisition and diagnostics techniques help pinpoint building performance symptoms, and verify that interventions have been effective. Courtesy Martha Hewett, Minnesota Center for Energy & Environment.



Outside air flows as a percent of required air flow for current occupancy and ventilation standards, 12 rooftop units at an elementary school.



Excessive head pressure (dark blue) and VFD speed (yellow) due to improper control of chilled water pump and of blending valve at connection with district chilled water system, high rise office building. Control strategy was changed 6/19 or 6/20/03. Data from BAS trends and portable data loggers.



Hunting of hot deck temperatures in triple-duct system (hot-cold-neutral; three distribution systems) with pneumatic control due to sensor thermal mass, steam valve sizing and controller proportional band. Data collected with portable data loggers. Older high-rise office building.

Historical Roots and Current Drivers of Commissioning

The notion of commissioning is said to have been born in the shipbuilding industry, subsequently emerging within the buildings sector in the late 1980s, with emphasis on indoor air quality and reconciling mechanical system performance with design intent (Piette *et al.* 1995). Only in the past decade has commissioning been routinely applied to energy-related considerations. Results from the Energy Edge program in the Pacific Northwest were one of the first significant "wake-up calls" that energy efficiency measures did not often work as well in practice as suggested by engineering calculations (Piette *et al.* 1994).

Commissioning has far broader relevance for energy management than simply optimizing energy-efficient systems. In new and existing buildings alike, energy efficiency can be enhanced in two major ways, either by ensuring and maximizing the performance of specific energy efficiency measures or by correcting problems that cause elevated energy use in "conventional" systems. Historically, the original focus of buildings energy commissioning efforts was centered on the former case—i.e., limited to specific energy efficiency measures—but has expanded to address the significant opportunities presented by the latter case.

Recent trends in the buildings construction and operations arena are elevating the importance of commissioning. For example, construction observation is less common today than in the past, and value engineering increasingly results in ill-informed, last minute design changes (as a result of efforts to trim project budgets) that can have adverse and unintended impacts on building performance and energy use.[2] The industry has become more fragmented and an increasingly competitive market environment has forced buildings-sector professionals to reduce fees and "streamline" services (Friedman *et al.* 2002). As a result of the preceding factors, building documentation and functional testing—the grist of the commissioning process—have been drastically curtailed. Meanwhile rising energy expenses, concerns about moisture problems, and increasingly complex mechanical and control systems are creating a greater need for systematic approaches to design and performance assurance.

Following are some of the major initiatives that have been mounted to expand the use of energy-oriented commissioning in commercial buildings. These include utility programs, national voluntary programs, promotion by professional societies, inclusion in building codes, and direct initiatives from building owners. Some examples follow:

- The federal government played a leading role in building the market for commissioning in the United States by requiring federal agencies to develop a commissioning plan for their buildings under the U.S. Energy Policy Act of 1992 and Executive Order 12902 (1994).
- One of the earliest scoping documents was Portland Energy Conservation, Inc.'s National Strategy for Building Commissioning (PECI 1998).
- The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has focused on commissioning, and issued an HVAC commissioning guideline (ASHRAE 1989).

[2] As an indicator of this phenomenon, insurance companies are seeing greater incidences of claims related to mechanical systems among newer buildings (Mills 2003).

- Numerous energy utilities have established commissioning incentive programs, the first of which was probably PacifiCorp (beginning in 1991), in which full rebate payments were not provided until major deficiencies were corrected. Utility initiatives for existing buildings have recently become more widespread, with programs in Oregon, California, Minnesota, Colorado, Connecticut, and Texas.
- The ENERGYSTAR Buildings Program was the first national voluntary initiative to integrate commissioning, as one of the five core steps.
- More recently, commissioning has become part of the "green buildings" movement, most notably as a prerequisite for LEED Certification (2000). LEED is probably the single most significant driver of new-construction commissioning in the U.S. today.
- In recognition of the erosion of energy savings caused by construction deficiencies, California building codes will soon require acceptance testing for certain systems.
- Commissioning has assumed a role in energy efficiency R&D at both the federal and state levels (e.g., the California Energy Commission's Public Interest Energy Research Program's activity on High-Performance Commercial Building Systems).
- The International Energy Agency has operated Annex 40, "Commissioning of Building HVAC Systems for Improved Energy Performance." Fourteen countries have participated.[3]
- "In-house" commissioning directives are also emanating from the private sector. For example, Johnson & Johnson has set a goal of 14% greenhouse-gas emissions reductions by 2010. Among its top-10 mandates to business units are building tune-ups (#2) and commissioning (#7). Other early adopters in the private sector include Westin Hotels, Boeing, Chevron, Kaiser Permanente, Disney Development Corporation, and Target (PECI 1998).
- The Building Commissioning Association is the first professional society of commissioning practitioners.[4]
- PECI organizes a well-attended national commissioning conference each year.

Commissioning has received increasing attention as the evaluation of energy efficiency programs has focused on measurement and verification of estimated and anticipated savings estimates. The commissioning movement has attained considerable momentum, and, as pointed out by Ryan and Nichols (2004) the issue is becoming more important as building energy management strategies become more sophisticated:

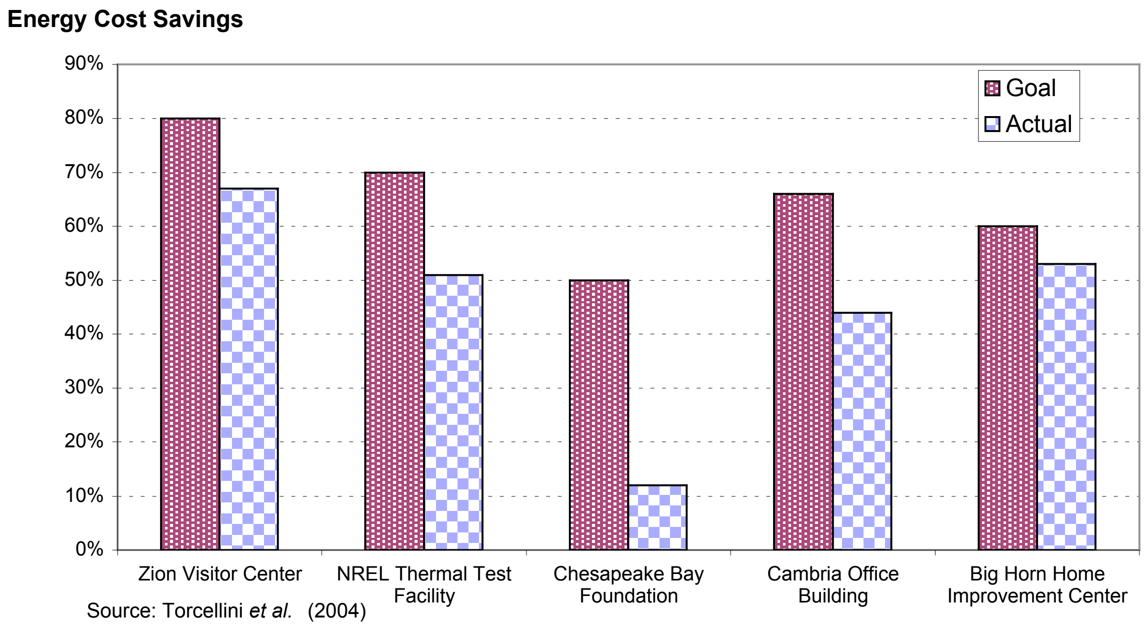
> *Even at the building component level, actual performance in real buildings may differ from predicted performance because of differences in installation, operation and other factors. This can lead to much lower energy savings than an optimal analysis would predict. Systems integration approaches, because they are considerably more complex than component approaches, present greater challenges. More complexity increases the probability for errors in design and execution, and thereby for greater divergence between design intent and actual building performance.*

[3] Participating countries include: Belgium, Canada, Finland, France, Germany, Hong Kong PRC, Hungary, Japan, Korea, Netherlands (Observer), Norway, Sweden, Switzerland, USA. See http://www.commissioning-hvac.org/

[4] See http://www.bcxa.org

Figure 1 exemplifies the problem, in the context of limited success in efforts to design and build six "high-performance" buildings." Issues included inaccurately stipulated insulation levels, installation of incorrect window frames, thermal short-circuits in building envelope, deficient lighting control calibration and algorithms, malfunctioning ventilation controls, poorly located exhaust dampers, and temperature setbacks out of compliance with design intent. While commissioning would not have entirely closed the gap between expected and actual performance for these buildings, it would have made a significant contribution towards doing so.

Fig 1. DOE High-Performance Buildings Case Studies: Goals v. Actual

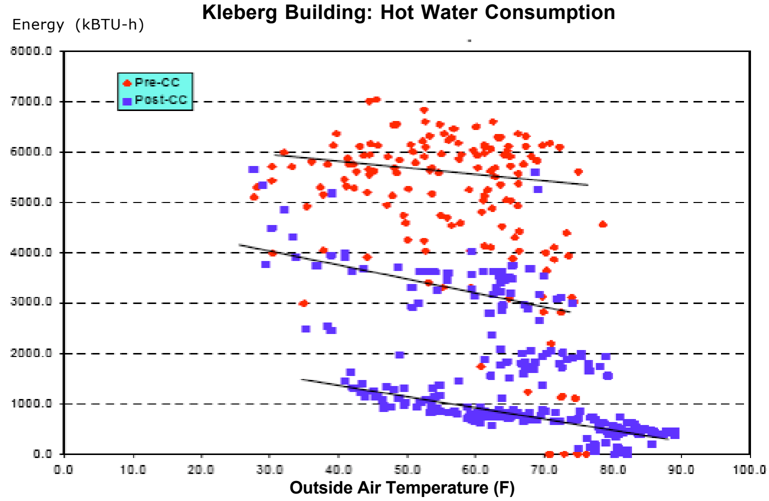


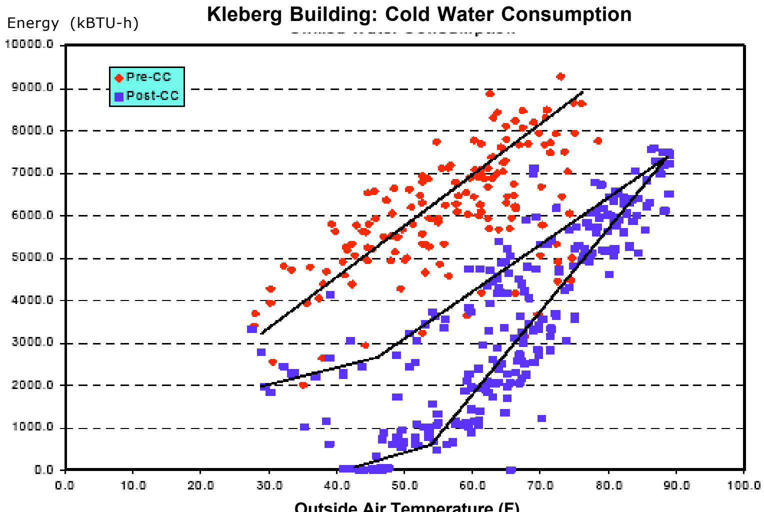
A specific case study of the need for and effectiveness of energy-oriented commissioning in existing buildings is provided in Figure 2. Here, a 165,000 square-foot building at Texas A&M University was found in an initial state with extensive simultaneous heating and cooling. By the time commissioning was completed, 64-percent chilled water savings and 84-percent hot water savings were achieved, with a value of $314,000 per year in reduced energy bills. The corresponding payback time was well under one year.

Current State-of-The Art

While individual building components are commonly tested or rated in a standardized factory setting (e.g., COP ratings for heat pumps), integrated assemblages of such technologies—which include important "connective" systems such as thermal distribution or controls systems—are rarely tested in the field. In its broadest sense, the practice of commissioning involves a series of systematic procedures and tests to ensure that new and existing building processes, technologies, and systems are applied and function in an integrated fashion as intended by the designer and desired by the owner. However, in practice, commissioning is rarely comprehensive (e.g., focusing only on specific pieces of equipment, or hampered by lack of budget or late commencement of the process).

Fig 2. Example of Energy Impacts of Existing-Buildings Commissioning





Source: Claridge et al. (2002)

INITIAL CONDITION (upper [red] clouds of data):
• Preheat was operating continuously, heating mixed air entering the cooling coil to approx 105F. This was being done intentionally to address a humidity problem in the building.

PHASE 1 MEASURES (middle [blue] clouds of data):
• Preheat turned off, and heating and cooling energy use dropped by ~ 1MBTU/hour (middle clouds)

PHASE 2 MEASURES (lower [blue] clouds of data):
More thorough examination of building resulted in the following interventions:
• Preheat turned from "off" to "preheat to 40F"
• Cold deck schedule changed from 55F fixed to 62 to 57F (variable as ambient varies from 40-60F)
• Economizer set to maintain mixed air at 57F whenever outside air below 60F
• Static pressure control reduced from 1.5 in H2O to 1.0; night-time setback to 0.5
• Replaced or repaird a number of VFD boxes
• Turned on chilled water pump VFDs
• CHW pump control changed so that one pump modulates to full speed before second pump comes on
• Building stack pressure reduced
• Fume hood exhaust pressure reduced

IMPACTS
• Chilled water: 64% reduction
• Hot water: 84% reduction

$314,000 annual energy cost savings

Commissioning is critical to ensuring the new technologies function and achieve optimal energy savings while maintaining or improving other aspects of building performance. More specific approaches to energy-oriented commissioning differentiate between applications in new construction and existing buildings as follows:

- New-construction commissioning (either of a new building or major renovation), and involves a quality assurance process ideally beginning at project inception and continuing through documentation of design intent, construction, startup, and operator training. The emphasis is on holding contractors to the requirements of their contract documents, and, in its ideal form, enabling clients (building owners) to articulate their expectations for measurable performance and quality assurance up front. From a technical standpoint, commissioning goes beyond conventional testing-and-balancing, with emphasis on systems-level interactions and functional testing to determine how well systems are working and to verify that design intent has been met or enhanced (and, if not, to make corrections). Examples of problems identified during commissioning include: design problems (e.g., equipment sizing errors), installation problems (e.g., construction debris blocking ventilation pathways), software problems (incorrect sequence of operations or control algorithms), hardware/manufacturing problems (inaccurate sensors), component failure (e.g., faulty control boards in EMS), or improper start-up (e.g., air in water systems resulting in cavitation or improperly adjusted daylighting controls).

- Existing-buildings commissioning involves identifying and remedying problems in specific components or systems and the optimization of these systems. The scope can be quite broad. Much as cars are "tuned up" on a regular basis, so too can buildings be commissioned with some frequency. Examples of problems identified during commissioning include: simultaneous heating and cooling, frozen valves, stuck dampers, fouled filters, over-ridden or malfunctioning variable speed drives, sub-optimized temperature controls, and excessive equipment cycling (damper operation, compressors, etc.). In some cases, the deficiencies are inadvertent, while in others they are the result of intentional efforts to circumvent other malfunctioning systems or to implement stopgap attempts to address occupant complaints. Existing-buildings commissioning has also shown to save considerable amounts of energy, even when performed after energy-savings retrofits have been implemented (Claridge *et al.* 2002).

There is of course a continuum across which both new-construction and existing-buildings commissioning techniques and perspectives are relevant. For example, when a new HVAC system is installed as a "retrofit" to an existing building, many of the issues normally associated with new-construction commissioning apply. Several important factors are held in common, e.g., in both cases the building owner must be the core proponent and driver, design intent documentation should be prepared, and construction observation and functional testing serve as valuable tools for identifying deficiencies and verifying performance. Also, many owners initiate commissioning late in the construction process, the result of which can be that the recommendations involve correcting existing mistakes rather than intercepting them early in design or during construction.

Commissioning is on the one hand common sense, yet is uncommon in practice. The philosophy of commissioning is tailored to achieve several overarching objectives: clear definition of construction or retrofit goals, performing work properly the first time, assignment of responsibility, verification of completion, and paying attention to operations once construction is completed (Dorgan *et al.* 2002).

The Role of Commissioning in Building Performance

As distinct from routine operations and maintenance, the particular power of commissioning is in looking at systems-level problems, e.g., interactions between control systems and HVAC equipment. The scope of commissioning can span all aspects of buildings, including security, safety, structural integrity, indoor environmental quality, and energy performance.

The emphasis in this report is on energy performance, although many other areas are necessarily related. While commissioning is often done primarily for non-energy reasons (e.g., to address indoor air quality concerns), it is not necessary to decouple the two. For example, in case studies of commissioning activities in existing schools in Minnesota that were primarily intended to address indoor environment concerns (inadequate air supply), energy objectives were integral such that increased ventilation did not create a burdensome energy penalty (MNCEE 2001c-e).

With an aggregate annual energy bill of $120 billion in 2002 (USDOE 2004), the U.S. commercial buildings sector presents a considerable potential for savings. The commercial buildings sector is also worthy of attention given that it is the only energy end-use sector that has shown steady growth in energy intensity, with 17-percent growth between 1985 and 2000 and projected growth of 1.7% per annum to the year 2025 (Ryan and Nicholls 2004). For these reasons, building commissioning can play a major and strategically important role in attaining national energy savings goals, while helping to manage the risk of under-achievement. As technologies and applications change and become more complex in the effort to capture greater energy savings, the risk of under-performance will rise and the value of building commissioning will increase. Indeed, innovation driven by the desire for increased energy efficiency may itself inadvertently create energy waste if those systems are not designed, implemented, and operated properly.[5]

Commissioning offers different types of value for different actors in the buildings arena. For the owner or occupant, commissioning provides a third-party assessment of project quality, helping ensure a safe, healthy, and high-performance (low-cost) environment. For the building trades, commissioning can improve information flow among team members, avoid costly call-backs or change-orders, and increase the likelihood of client satisfaction. For the planner, policymaker, or utility official with a macro-level perspective, it serves as a risk-management strategy to ensure that programmatic goals (e.g., anticipated energy savings) are attained in fact (Mills *et al.* 2004).

Prior Cost-Benefit Assessments

Scattered case studies and anecdotal information form the basis of "conventional wisdom" within the buildings energy community that commissioning is highly cost-effective, i.e., with payback times ranging from several months to one or two years in most cases.

There is a growing body of literature documenting individual commissioning case studies for individual buildings, much of which is drawn upon in this study.[6] In addition, we compiled information from several previous studies that assembled data from multiple projects:

- Stum and Haasl (1994) performed what may be the first study comparing multiple buildings.
- Piette *et al.* (1995) performed a detailed cost-benefit study of 16 (mostly new and small) buildings commissioned under the PacifiCorp program. It was largely limited to the commissioning of 46 specific energy efficiency measures (as distinct from whole-system commissioning).

[5] Examples noted by Friedman *et al.* (2002) included evaporative cooling, demand-controlled ventilation, dimmable ballasts, dessicant cooling, and natural ventilation.
[6] Many of the earliest works did not isolate the costs of commissioning from those of the energy-efficiency measures being commissioned (e.g., Yoder 1994) and hence provide insufficient information of the type of analysis performed in this study.

- Gregerson (1997) compiled data on commissioning of 43 existing buildings, mostly in the Northwest (from PECI) and Texas (from TAMU). Minimal data were reported.
- A variety of agencies in the Pacific Northwest sponsored a compilation of new and existing buildings commissioning experience (PECI 1997a). About 175 buildings were examined, although only summary data were published in an extended brochure. No cost-effectiveness information was included and the results were collapsed into ranges, reported by building type.
- Wilkinson (2000) described 19 new-construction projects. Minimal data were provided.
- The Minnesota Center for Energy & Environment assembled 6 case studies of new and existing buildings in the state, some of which include cost-benefit information (MNCEE 2001a-f).
- As part of their "EBIDS" decision support tool, the Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon in partnership with the Lawrence Berkeley National Laboratory compiled and compared 11 case studies of existing-building commissioning, using the results to establish rules-of-thumb about best practices and the potential economic benefits of commissioning.[7]
- Most recently, the Northwest Energy Efficiency Alliance (NEEA) has conducted a major multi-year study of public buildings throughout the Pacific Northwest. The 13 new and 8 existing buildings were analyzed in great detail, including a thorough cost-benefit study (SBW and Skumatz 2003).

As described in the remainder of this report, we compiled approximately 7000 largely energy-related deficiencies identified across over 224 buildings. The good news is that, once identified, many of these problems were remedied in a cost-effective manner, yielding higher performance buildings – in some cases even exceeding the original aspirations of their designers.

Structure of This Report

We begin by outlining our methodology, generalizing the discussion in order to provide a recommended practice for others embarking on such analyses. We discuss data collection and analytical methods, decision rules, describing the commissioning process, quantifying costs, valuing energy savings, and characterizing non-energy impacts. The establishment of quantitative metrics is a key underpinning for the process.

We then proceed to a presentation of our results. This begins with various summary statistics, in which we characterize the buildings in our sample and their geographical distribution, with comparisons to the overall U.S. buildings stock, and provide top-level cost-effectiveness results. A detailed matrix of results, by metric, is provided, along with a quartile analysis showing median, min, max, and upper/lower 25th percentile results for each commissioning metric. We then separately present detailed results for existing buildings and new construction. These sections first describe drivers (reasons cited for commissioning), scope of the commissioning process, commissioning costs, and an in-depth look at the specific types of deficiencies discovered and the measures to remedy them. We analyze total energy savings and savings by fuel type. Using the results, we analyze various relationships, e.g., the cost and cost-effectiveness

[7] See http://cbpd.arc.cmu.edu/ebids

of commissioning as a function of building size. The results sections include discussion of available data on the rate at which savings materialize following commissioning as well as the persistence of those savings over time, and conclude with an analysis of the non-energy benefits reported by many of the projects.

Reflecting on the results, we then offer a discussion of caveats and conservatisms, such as sources of uncertainty or over-prediction of savings, as well as reasons why savings may be systematically underestimated.

We conclude with a recap of major findings and implications for energy policy, including a scoping estimate of the national energy savings potential and future research needs. The appendices provide specimen copies of our data instrument, documentation of various analytical assumptions, definitions of measures, and a catalog of summary information for the projects analyzed.

METHODOLOGY

Establishing Standard Data Definitions and Performance Metrics

In this section, we present our methodology and generalize the discussion in order to provide a recommended practice for others embarking on such analyses. The full data-collection instrument is shown in Appendix A, and the key assumptions and data decision rules in Appendix B. We evaluate existing buildings and new construction separately, as the issues and costs are qualitatively different.

Our approach begins with defining desired metrics and indicators (Box 3), and, from these endpoints, the types of data required to enable the analysis. It is important to consider and define the desirable metrics in advance of data collection efforts. Given the tendency towards extreme but rare outliers for many of the metrics, we utilize the median values rather than the average to characterize the central tendency for indicators summarizing the data, and quartile analysis to provide a sense of the variability in results.[8]

As commissioning is a highly variable process, it is important to develop a consistent and sufficiently specific framework for describing the problems (deficiencies) discovered through the commissioning process and the measures applied to address them. We developed the "Measures Matrix," shown in Table 1, which captures information on deficiencies and characterizes a specific commissioning measure with a unique code; field definitions are provided in Appendix C.[9] Many of the fields were derived from the data collection protocols for new and existing buildings developed by an Experts Workshop directed by the California Commissioning Collaborative (Friedman *et al.* 2004), from which we extracted data elements relevant to our analysis objectives. As the CCC database is limited to California buildings, requires extensive documentation, and its analytical routines are not yet implemented, it was not used directly for this study. We completed Measures Matrices for 71 existing buildings and 20 for new construction.

Comparing numbers of deficiencies and measures across projects is problematic given the semi-arbitrary ways in which they can be counted (e.g., is an installation error affecting 100 terminal boxes counted as one or one-hundred deficiencies?). Moreover, sometimes only a subset of measures is included in commissioning documentation or evaluations. For example, SBW and Skumatz (2003) tabulated 1616 deficiencies across 21 projects, but only tabulated and analyzed the subset of 235 (14.5%, and as few as 3% for one project) that were considered to be "significant".[10]

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[8] The median a value in an ordered set of values below and above which there is an equal number of values or which is the arithmetic mean of the two middle values if there is no one middle number. The median is thus less distorted by extreme upper or lower limits than is the average.

[9] Naoya Motegi of LBNL developed an early version of the "Measures Matrix", which we expanded and adapted for this study.

[10] The study's definition of significance included all issues that affected a large area or number of people in the building, and/or resulted in major costs to resolve or major benefits over time.

Table 1. Example of Measures Matrix used to characterize commissioning projects.

Project A. Hospital Facility

	Components (locus of fault)										Measures																				
											Design, Installation, Retrofit, Replacement				Operations & Control									Maintenance							
	HVAC (combined heating and cooling)	Cooling plant	Heating plant	Air handling & distribution	Terminal units	Lighting	Envelope	Plug loads	Facility-wide (e.g. EMCS or utility related)	Other	Design change	Installation modifications	Retrofit/equipment replacement	Other	Implement advanced reset	Start/Stop (environmentally determined)	Scheduling (occupancy determined)	Modify setpoint	Equipment staging	Modify sequence of operations	Loop tuning	Behavior modification/manual changes to operations	Other	Calibration	Mechanical fix	Heat transfer maintenance	Filtration maintenance	Other			
	V	C	H	A	T	L	E	P	F	O	D1	D2	D3	D4	OC1	OC2	OC3	OC4	OC5	OC6	OC7	OC8	OC9	M1	M2	M3	M4	M5	Measure Code	Implemented [Y;N;?]	Detail problems and remediation measures
			x																					x					H-M1	Y	Setpoint controller on boiler 1 was out of calibration by 20F
				x																x									A-OC6	Y	Night low limit should only control perimeter boxes with reheat, not core boxes
						x											x												L-OC3	Y	All exterior lighting ON all night per programming. Changed outside lighting to OFF at 2:45 am.
				x											x														A-OC1	Y	Discharge air temperature reset schedule was not programmed. Added reset schedule.
				x														x											A-OC4	Y	Cooling-only VAV box min setting supposed to be 0, but set at 56%. Simultaneous heating and cooling with an adjacent zone.
				x														x											A-OC4	Y	Differential omitted from night high limit sequence and night low limit sequence. Causes cycling of AHU.
				x																x									A-OC6	Y	Outside air dampers don't close during optimal start and night low limit
	x																											x	V-M5	Y	Poor system documentation. Unclear and incomplete control sequences. Did not include flow rates for control valves or location of duct smoke detectors and backflow preventers. Improved documentation for O&M manuals
			x															x											H-OC4	Y	Firing rate controller setting on both boilers were wrong. High limit supposed ot be 20F>low limit. It was reversed.
				x																x									A-OC6	Y	Confusion as to what the BAS will control and what the Trane RTU will control. Got it straight and programmed.
									x														x						F-OC9	Y	Current trending capability is limited to 1 parameter per trend and can only be viewed one parameter at a time. Inconvenient for troubleshooting and fine tuning.Got new interface with full graphing capabilities.
			x									x																	H-D2	Y	Isolation valves to boilers missing. HW supply temp cannot be controlled or maintained by mixing valve when only 1 boiler is on. Valves and controls added.
					x																			x					T-M1	Y	Nine out of the nine thermostats were out of calibration. JCI didn't use a calibrated thermometer and used +/- 2F as acceptable. JCI sensors used are rated to +/- 0.5F, specs call for +/- 0.5F calibration.
			x																				x						H-OC9	Y	Alarms on boilers had been disabled. Enabled alarms.
				x								x																	A-D2	Y	ASU-1 & 2 didn't have duct static pressure sensors hooked up.
	x																							x					V-M1	Y	OAT sensor calibration 2.5 degrees off. Recalibrated.
	x											x																	V-D2	Y	Installation problems: : ductwork high SP loss fittings, duct sealing, sheetrock dust on coils, exhaust fan not wired, valve not hooked up, timeswitch doesn't start fan, fan coil won't start by adjusting thermostat, TU zero calibration not enabled, exhaust duct not connected, disconnects on boilers missing
									x											x									F-OC6	Y	Power outage sequences: not programmed correctly
					x							x																	T-D2	Y	Duct crushed 12" from TU inlet to make room for sprinkler pipe. Erratic TU flow control. Sensor relocated.
Other:																														Y	93 Other findings not tabulated
Rejected																															
Count or total:	3	0	4	7	2	1	0	0	2	0	0	4	0	0	1	0	1	3	0	4	0	0	2	3	0	0	0	1			
Grand Totals:	19										19																				

Note: "Measure Code" is a unique code assigned based on each measure's corresponding deficiency and type. The full Measures Matrix also contains fields for persistence, savings measurement method, and energy impacts.

Box 3. Commissioning Metrics

Building Characteristics and Demographics
- Building type (using DOE/CBECS definitions), vintage, location
- Year building commissioned
- Scope of commissioning (per pre-set typology of steps)
- Reasons for commissioning, deficiencies identified, measures recommended

Energy utilization intensity (use or savings)
- Electricity: kWh/building,[11] kWh/ft^2-year
- Peak electrical power: kW/building; W/ft^2
- Fuel: MMBTU/building; kBTU/ft^2-year
- Purchased thermal energy: MMBTU/Building; kBTU/ft^2-year
- Total energy: MMBTU/building; kBTU/ft^2-year[12]
- Energy cost: $/building-year; $/ft^2-year (based on local or standardized energy prices; nominal and inflation corrected to a uniform year's currency levels)
- Percent energy use savings (total and by fuel)
- Percent total energy cost savings
- Persistence index$_i$: Post-commissioning energy use in a given year, "i"/pre-commissioning energy use (unitless ratio)

Commissioning cost
- $/building; $/ft^2 (based on nominal costs or, preferably, inflation corrected to a uniform year's currency levels. Can be gross value or net, adjusting for the quantified value of non-energy impacts)
- Commissioning cost ratio, for new construction (commissioning cost / total building or renovation construction cost, %).[13]
- Costs are tabulated separately for the commissioning agent and other parties
- Allocation of costs by source of funds (building owner, utility, research grant, other)
- Total building construction cost (denominator for commissioning cost ratio)

Cost effectiveness
- Undiscounted payback time (commissioning cost/annualized energy bill savings). This indicator is preferably normalized to standard energy prices; costs and benefits are inflation corrected to a uniform year's currency levels

Deficiencies and measures
- Deficiencies/building; Deficiencies/100kft^2
- Measures/building; Measures/100kft^2
- Unique codes to identify combinations of deficiencies and measures (described in more depth below)

Commissioning scope
- Presence of pre-defined "steps" (yes/no), with different criteria for existing buildings and new construction

Non-energy impacts
- Type
- Quantified (when possible), $/building; $/ft^2-year [can be positive or negative]
- Yes/No (when not quantified)

[11] In some cases, multiple buildings will be aggregated, in which case data must be analyzed at the "project" level.
[12] Throughout this report, electricity is counted in "site" energy units, excluding losses in generation, transmission, and distribution, i.e., 3412 BTUs/kWh.
[13] Commissioning cost as a percentage of total electrical or mechanical costs is often used as well (Wilkinson 2000).

There are many figures of merit for characterizing commissioning cost-effectiveness. These include net present value, benefit/cost ratio, return on investment, levelized cost of conserved energy, increased asset value, and simple or discounted payback times. For the purposes of the analysis described in this report, we have chosen the simple payback time. This indicator is intuitive and familiar to the intended audience. Given the short payback times typically associated with commissioning, discounting adds little value and introduces uncertainties and points of debate regarding the "correct" discount rate. In addition, the cost-effectiveness level of measures with relatively short payback times (as encountered in this review of commissioning experience) is not influenced by changes in energy savings beyond the payback time, whereas "life-cycle" indicators such as net present value must include treatment of the highly-uncertain issue of savings persistence. Finally, use of payback time does not require stipulation of commissioning measure lifetime, a highly uncertain factor. The key shortcoming of payback time, on the other hand, is that benefits beyond the payback period are not quantified.

Data Collection and Methodological Approaches to Cost-benefit Analysis

We reviewed publications from the open archival and grey literature and commissioning-provider project files to identify commissioning projects that were sufficiently well documented to enable an analysis of cost-effectiveness and other factors of importance in this study. Use of the grey literature is essential for a study such as this, given that property owners who obtain commissioning services rarely fund formal publication of the process and results. Not surprisingly, some of the most well documented material is brought to light when projects are conducted under public-interest sponsorship, as illustrated by the case of Bonneville Power Administration's funding of case study reports on commissioning at the University of Washington (Caner 1996; 1997).

Conducting cost-benefit analysis of commissioning is arguably more difficult than for conventional hardware-oriented energy efficiency strategies. There are more factors on both the costs and benefits side of the equation—particularly non-energy impacts—and definitional issues are not as clear-cut. Quantifying energy savings can be more difficult, as the measures typically involve multiple systems and controls within the building as distinct from a single piece of equipment. Analyzing new construction is particularly difficult, given the absence of a measurable "no-commissioning" baseline. Commissioning measures are less likely to persist than hardware measures.

Only in the past few years have efforts been made to establish a robust framework for commissioning cost-benefit analysis. Some of the previous efforts have been conceptual in nature, while others have developed and applied an explicit methodology. Wilkinson (2000) pointed out the need for consistent methods of estimating new-construction commissioning costs. Altweis and McIntosh (2001) and Cohan and Willems (2001) appear to be among the first to have articulated specific frameworks for characterizing commissioning costs and benefits. [14] Willems encouraged analysts to present a range bounded by "most likely" costs and the "least-cost" solution. Veltri (2002) also offered a methodology. The most thorough framework we have

[14] As mentioned above, Friedman *et al.* (2004) are developing such a framework for use in the California context.

encountered is that developed for evaluation of the "Costs and Benefits of Commissioning in Public Buildings Project" being conducted in the Pacific Northwest (SBW and Skumatz 2003). Their framework included consideration of one-time and ongoing costs and benefits, a detailed methodology for valuing non-energy impacts, and use of standardized energy prices.

Friedman *et al.* (2004) provide an extensive discussion of determining which costs should and shouldn't be ascribed to the commissioning process. We summarize and augment that work in Table 2. While in some cases the costs arising from the commissioning process (e.g., correcting design flaws) should not be included in the costs of commissioning, the benefits are, in principle, associated with the commissioning process if the issue would not otherwise have been identified and remedied – this, however is very difficult to determine in practice.

Table 2. Rules for inclusion of costs in scope of commissioning.

Cost Factor	Include Cost?	Relevance (**N**ew Construction, **E**xisting buildings)	Examples
Cx provider's fixed costs	Yes	N; E	Costs of developing commissioning spec, reviewing design documents, conducting inspections, construction observation
Other contractors' costs			
Contract compliance	No	N; E	Construct building; install systems
Testing and balancing (TAB)	No	N; E	Preceeds commissioning; separate service with separate fees
Coordination with commissioning provider	Yes	N; E	Assist in performing functional tests
Correcting design flaws	No	N	Included in design contract and warranty
Improving design or operations	Yes	N	Recommendations to reduce pressure-drop, improved control sequences
"Non-billable" in-house operations staff fixed costs	As desired by owner	N; E	Staff time to work with commissioning provider
Functional tests	Yes	N; E	Validating intended damper positions or variable-speed drive operating cycle
Resolution costs related to optimizing systems	Yes	N; E	Corrections during start-up; tune-up
Costs related to ensuring other trades' adherence to contract documents	Yes	N; E	Verifying as-built condition meets design intent
Resolution costs related to installing a system beyond project scope	No	N	Installing energy management and control systems; major capital retrofits
Resolution costs related to operations and maintenance	Yes	E	Cleaning fouled filters
Minor capital improvements to resolve deficiencies	Yes	N; E	Operations and maintenance
Major capital improvements to resolve deficiencies: new construction	No	N	Replacing incorrectly sized chiller
Major capital improvements to resolve deficiencies: existing buildings	Yes	E	Replacing faulty control system elements
Training or on-site staff	Yes, if in scope	N; E	
Utility rebates, grants, or other external financial assistance	Yes	N; E	Represents part of true project cost
Research-related costs	No	N; E	Development of research reports; not essential to efficacy of commissioning project
Travel	Yes	N; E	To and from project site
Non-energy impacts	Yes	N; E	Often not quantified

While prior work in this area has identified and addressed many important considerations, none of the methodologies we encountered considered the importance of normalizing economic analyses to common units when comparing among disparate project costs and savings. Two key elements include correcting for inflation so as to meaningfully compare projects occurring across long periods of time, and normalizing for variations in energy prices across projects. To illustrate the importance of this variable, nominal (non-inflation-corrected) energy prices varied widely across our sample: electricity from \$0.025 to \$0.159/kWh, fuel from \$2.50 to \$10.22/MBTU, and hot/chilled water from \$2.58 to \$8.30/MBTU.

Many studies normalized results by floor area, but were limited in their characterization of the breadth and depth of commissioning. Some studies combine results for new-construction and existing buildings; given the material differences between these two forms of commissioning we do not view this as appropriate or meaningful. Irrespective of the approach, documenting assumptions is of overarching importance, yet few published studies do so, rendering the analysis non-replicable and non-auditable.

A thorough approach to identifying and evaluating the cost and cost-effectiveness of commissioning has a number of major components, described in below.

Characterizing Building Features

When the aim is to compare projects, it is important to standardize the definitions used to characterize the buildings. For comparisons to the broader building stock, building types must be defined. Given that the best national energy data for the commercial buildings sector are provided by the U.S. Department of Energy's Commercial Buildings Energy Consumption Survey (EIA 1999), we utilized their definitions, which divide the sector into 15 building types.

As with most energy normalization and benchmarking activities, defining floor area is typically a key factor, as is the treatment of indoor parking areas. Consistent definitions must be adopted. In this study, we utilize only the area affected by the commissioning activity (which may be less than the entire building area). Where available, we utilize the area net of indoor parking space.

Describing the Scope of Commissioning

Commissioning activities need to be clearly defined, and those definitions applied consistently to ensure maximally inter-comparable results across projects. The commissioning process can range from being highly limited (either superficial and/or limited in scope, e.g., focusing on a single building sub-system or piece of equipment) to highly comprehensive. For new construction, commissioning can follow the entire design-build-startup process, but is often introduced only at a late stage. The documentation of project scope—steps included in the commissioning process—was collected when available (this included 69 percent of the existing buildings studied and 38 percent of the cases of new construction). We identified fifteen potential steps for existing-buildings commissioning and sixteen steps for new-construction commissioning.

Analysts often incorrectly include costs that are not appropriately ascribed to commissioning, e.g., testing-and-balancing, TAB, (which is a service in and unto itself, distinct from commissioning). However, commissioning may help reduce TAB costs and time requirements, in which case the benefit could be credited to commissioning (Caner 1996). Several commissioning projects explicitly set out to improve the TAB process, e.g., by preparing an improved TAB specification (MNCEE 2001c-e).

Quantifying the Costs of Commissioning

Care should be taken to include all relevant costs born by all parties (although it may be of interest to conduct sub-analyses to evaluate the implications for different actors). Commissioning may be funded by any combination of the building owner, tenant, utility, or other third parties such as providers of research grants. Commissioning may be implemented by various parties, including but not limited to the “Commissioning Agent”. An important “grey area” is the cost of labor for in-house participants. The Northwest Public Buildings study (SBW and Skumatz 2003) refers to these as “indirect” costs (but we include them as “core” costs here). If the owner does not consider in-house personnel costs as a additional costs, they are not included in our definition of commissioning costs, for example in the case of involving operators during functional testing as a method of training in-house staff. In this study, we utilize the construction labor cost index published by the U.S. Bureau of Labor Statistics (2004) (Appendix B) to normalize commissioning costs to year-2003 prices. Travel is another cost item that should be tabulated.

Commissioning costs can be normalized by floor area. For new construction, they are also often expressed as a percentage of the total construction cost and/or mechanical system cost. In either case, the construction cost should be normalized to a standard year’s currency. In this study, we use the McGraw-Hill Construction Cost Index for this purpose (Appendix B).[15]

Attention should also be paid to the fact that commissioning is often done for non-energy reasons (e.g., directed at security systems). For example, respondents to a baseline survey in the Pacific Northwest ranked energy savings seventh among overall (energy and non-energy) perceived benefits of new-construction commissioning (Willems 1999). While energy savings are not always a prime motivator of commissioning, energy-using systems are often at the root of problems that commissioning providers seek to remedy. Commissioning costs thus typically encompass measures that do not save energy, yet the economic value of non-energy impacts is rarely quantified. This leads to an under-estimation of the cost-effectiveness of commissioning.

For existing buildings, costs for remedying deficiencies are often included–at least to a degree –given that the party responsible for the error is typically no longer under contract or otherwise available and liable to provide the remedy. Judgment needs to be applied in attributing these costs to commissioning versus routine maintenance or retrofit. Some studies (e.g., SBW and Skumatz 2003) have taken a conservative approach for some of their projects, heavily attributing these peripheral costs to the commissioning process. For new construction, many corrections can be recharged to the original contractor under warranty agreements, and thus should not be debited to the commissioning process.

Many commissioning projects are conducted under public- or privately-funded research programs. This incurs extra costs for experimental design, analysis, and perhaps instrumentation that would not ordinarily be called for. In these cases, the relevant research costs should be isolated from routine commissioning costs and, if deemed appropriate, excluded from the core analysis, as we have done in this study where the data were available.

From a practical perspective, there is no one single “correct” range of costs to be included. This will depend on the audience for the analysis, e.g., a building owner may want to exclude utility rebates or financial assistance from other parties, as it is not an out-of-pocket cost, whereas a policy analyst or program evaluator would likely want to include such costs. Of primary importance is that a standard definition is used when comparing multiple projects. Using the rules laid out in Table 2, we have standardized definitions, to the extent allowed by the source data.

[15] See http://enr.construction.com/features/conEco/costIndexes/constIndexHist.asp.

Quantifying Energy Savings

While a discussion of the methods of estimating or measuring energy use and savings are beyond the scope of this report, they are clearly central to the question of assessing cost-effectiveness. As this is a meta-evaluation, we did not perform primary energy data collection and analysis. However, we did capture information on the methods used to determine savings. Piette *et al.* (1995) and others provide detailed discussions about estimating commissioning energy savings for new or existing buildings. Various methodological issues are important to keep in mind when attempting to quantify energy savings from commissioning, including:

- When working with existing buildings, measured savings data may be available. In our sample, 69 of the 106 existing-building projects had measured weather-normalized data. We limited comparative pre-/post-commissioning analyses to cases with weather-normalized data; we used all data based on engineering estimates, as weather is not a confounding factor for comparisons. Where multi-year post-commissioning energy data are available, we noted that energy savings may not manifest fully in the first post-commissioning year, as implementation can be gradual.

- Once savings have fully emerged, they may subsequently decline (persistence problems). Although savings tend to last sufficiently long for the original commissioning costs to be recovered, it is desirable to monitor energy use over a multi-year period to track persistence and identify "flags" signaling the need for another cycle of commissioning.

- In rare instances, energy use can increase as a result of commissioning, e.g. when a non-functioning piece of equipment is discovered and repaired. Box 2a provides another example: the discovery of under-ventilation.

- The quality of data varies. In this study, we characterize the data as measured or estimated, and, within the former category, record the category of measurement per the International Performance Measurement and Verification goals, as shown in Appendix D (IPMVP 2001). The two cohorts should be analyzed independently.

- Savings cannot be directly measured for new-construction commissioning, as the "road not taken" represents a building completed without remedying the deficiencies found by the commissioning process. In this case, post-commissioning energy use may be measured, but savings can only be estimated, e.g., by engineering calculations or more sophisticated modeling of the proposed building with and without the deficiencies resolved (Piette *et al.* 1995).

- Irrespective of the method of determining energy savings, it should be kept in mind that the commissioning report's recommendations may be in the process of being implemented at the time energy savings data are collected. If estimates of ultimate savings are available, they should be incorporated in cost-benefit analyses. However, attention must be given to the fact that not all recommendations will necessarily be implemented as of the time of evaluation, especially since primary documents (e.g., commissioning reports) are typically created immediately upon delivery of the recommendations. In this study, we attempted to exclude savings for measures not known to have been implemented, but otherwise included savings for measures that had not yet been implemented as of the date the project was documented. An important caveat is that few of the primary sources quantified the benefits of all identified savings opportunities.

Valuing Energy Savings

Once the quantity of energy saved is determined, the value depends on the assumed energy pricing and tariffs. If commissioning cases are to be inter-compared, computing energy costs using a single set of energy prices is highly desirable. If it is preferred to retain local energy prices, those prices should at a minimum be inflation-adjusted to a common year using an energy price index. In this report, we do both, i.e., we derive an index from the nominal historical price trajectories published by USDOE/EIA and normalize to year-2003 currencies. As noted above, because of differences in time and location across our sample, variations in the nominal energy prices underlying the raw cost savings values were considerable, e.g., electricity prices varied by a factor of six.

Characterizing Non-energy Impacts: Costs and Benefits

Perhaps the largest caveat in any cost-benefit analysis for commissioning is that energy savings are only one of many quantifiable and non-quantifiable impacts (Table 3). Non-energy impacts (NEIs) include but are not limited to changes in maintenance costs, changes in equipment lifetime, improved productivity, reduced change orders, and improved indoor air quality. Such impacts can be positive or negative.

Non-energy impacts are important determinants of whether a building owner seeks commissioning services. As an example, a principal in the commissioning of four major laboratory buildings in Seattle, Washington noted that the primary goal of commissioning was occupant safety, followed by productivity of academic research, followed by teaching, comfort and public relations, and *then* energy (Caner 1996 and 1997). Given the definitional and quantitative uncertainties surrounding non-energy benefits, analysts may elect to present cost-benefit analyses with and without these factors, as we do in this study.

If non-energy impacts are quantified, they can be incorporated in cost-benefit analysis. A method for doing so was employed by SBW and Skumatz (2003) in their study of commissioned public buildings in the Pacific Northwest. The method involved interviewing 97 commissioning team members across 21 projects and having them gauge the value/costs of non-energy impacts in relation to a known direct cost associated with the project, i.e., the commissioning fees, and weighting the answers depending on the source of the vote and the qualitative level of importance that each respondent assigned to the impact. The study found average annual non-energy commissioning benefits of $0.26 per square foot for existing buildings and benefits of $0.17 per square foot for new construction.

Table 3. Energy and non-energy impacts (positive or negative) of commissioning.

	Cost	Benefit	Comment
Direct			
Cost of (retro)commissioning service	x	x	Cost can be partially or completely offset by the indirect effects listed below
Energy consumption	x	x	In rare circumstances, energy use can increase if equipment is found in "off" or under-utilized state
Indirect			
Accelerated repair of a problem (assuming it would have been identified and corrected, eventually, without commissioning)		x	
Avoided premature equipment failure		x	
Changes in O&M costs	x	x	
Changes in project schedule	x	x	Can shorten or lengthen schedule
Clarified delineation of responsibilities among team members		x	
Contractor call-backs		x	
Occupant comfort/productivity		x	
Equipment right-sizing		x	
Impacts on indoor environment		x	
Documentation		x	
In-house staff knowledge		x	
Disruption to occupancy and operations		x	Early detection of problems
More vigilant contractor behavior (knowing that Cx will follow their work)		x	
Operational efficacy		x	
Potential for reduced liability/litigation		x	
Change orders	x	x	Timely introduction of commissioning (early in process); otherwise potential for increase
Disagreement among contractors		x	
TAB costs		x	Can be reduced by solving problems that the TAB contractor would otherwise have encountered
Safety impacts		x	
Warranty claims		x	
Water utilization		x	
Worker productivity		x	

Some specific examples of non-energy impacts include:

- Altweis (2002) describes the results of six projects, in which change orders were reduced by 87%, contractor callbacks reduced by 90%, and reduced construction cost by an undetermined amount (estimated 4 to 9 percent).

- Tso *et al.* (2002) found an average of 12 measures per project in new construction that resulted in extended equipment life and 9 measures in the case of existing buildings.

- The commissioning strategy undertaken as part of the Pentagon Renovation Project (not included in our compilation) is estimated to have resulted in $3 million per year in improved worker productivity (Cox and Williams 2000).

- Perhaps the most elusive non-energy impact is reduced liability or insurance claims. This is an often-cited benefit (Brady 1995; Tyler 1995; Martinez 1999) but is among the most difficult to quantify (as the outcomes of litigation are often confidential). Nelson (1999) states that twelve buildings-related claims – representing an aggregate award of $60 million—could have been avoided by proper commissioning. Insurance companies have endorsed commissioning as a way to avoid liability claims among architects and engineers (Mills 2003; Chen and Vine 1998).

RESULTS

Sample Characteristics

Our data collection efforts yielded 175 projects, spanning 21 states and representing 30.4 million square feet of floor area. The median building size was 151,000 square feet for existing buildings (95,101 to 271,650 square feet inter-quartile range) and 69,500 square feet for new construction (32,268 to 151,000 square feet inter-quartile range). The 104 projects providing the information represent the work of 18 known commissioning providers (Table 4); the provider is unknown for 16 percent of existing buildings floor area and for 62 percent of new construction floor area. With the exception of the "religious worship" and "vacant" categories, our sample covered all major building types identified in the US Energy Information Administration's periodic Commercial Buildings Energy Consumption Surveys[16] (Figures 3 to 5 and Table 5). As not all data elements were available for all projects, (Figure 6) summarizes the "sample depth" for a number of the key parameters.

Table 4. Commissioning providers, by floor area.

	Existing Buildings (square feet)	%	New Construction (square feet)	%
Affiliated Engineers, Inc. (Walnut Creek, CA)	-	-	774,000	9.5%
CH2M Hill (Portland OR)	-	-	340,000	4.2%
Environmental and Engineering Services, Inc.	-	-	160,000	2.0%
Facility Dynamics (Baltimore, MD)	1,014,133	4.6%	-	-
Facility Improvement Corporation (Great Falls, MT)	64,000	0.3%	-	-
Farnsworth Group	-		1,083,758	13.3%
HEC (ESCO)	376,500	1.7%	165,000	2.0%
Herzog/Wheeler	44,000	0.2%	-	-
Keithly/Welsch Associates Inc (Burien WA)	65,000	0.3%	144,000	1.8%
Nexant (San Francisco, CA)	210,406	0.9%	-	0.0%
Northwest Engineering Service, Inc.	213,000	1.0%	-	0.0%
PECI (Portland, OR)_	4,345,810	19.5%	371,000	4.5%
Quantum Energy Services and Technologies, Inc. - QuEST (Oakland, CA)	2,132,411	9.6%	-	-
Sieben Energy	623,000	2.8%	-	-
Systems West Engineers (Eugene, OR)	172,400	0.8%	-	-
TAMU/ESL College Station TX)	9,439,042	42.5%	-	-
Test Comm LLC (Spokanne, WA)	-	-	60,000	0.7%
Western Montana Engineering	-	-	23,300	0.3%
Other	3,531,592	15.9%	5,046,400	61.8%
Total	**22,231,294**	**100%**	**8,167,457**	**100%**

[16] See http://www.eia.doe.gov/commercial.html

Fig 3. States Represented by Projects in this Study

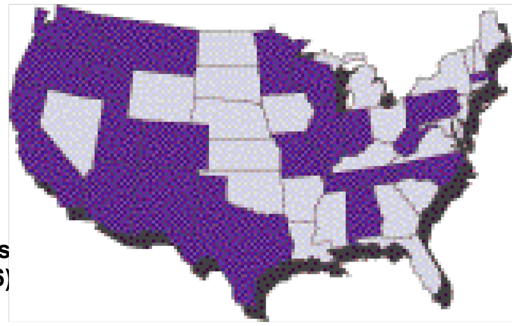


Fig 4a. Location of Projects (Existing Buildings, N=106)

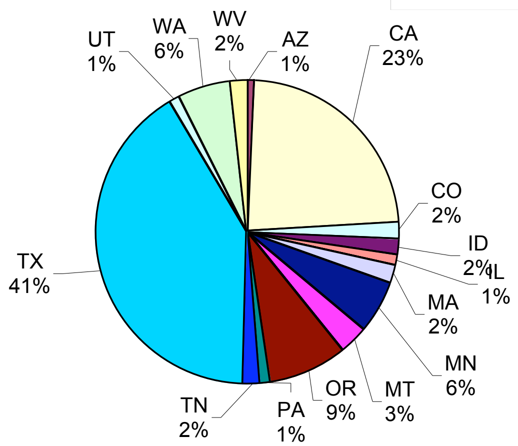


Fig 4b. Location of Projects (New Construction, N=69)

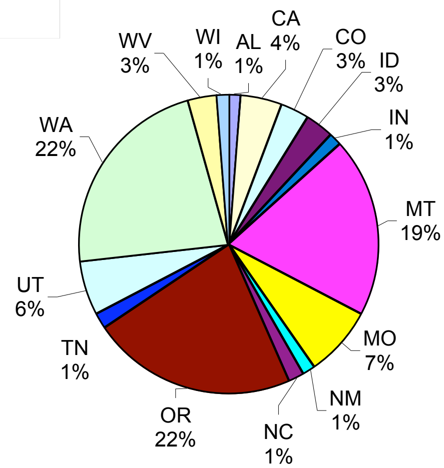


Fig 5. Sample versus U.S. Stock, by Floor Area (Existing Buildings and New Construction 30.4 million sq. ft.)

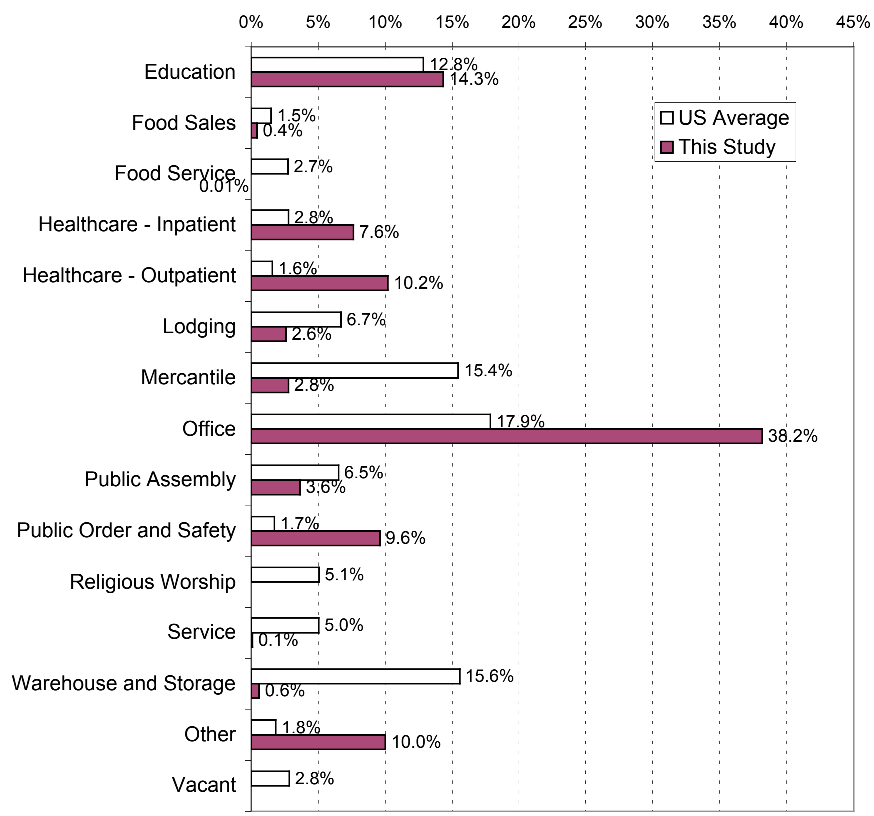
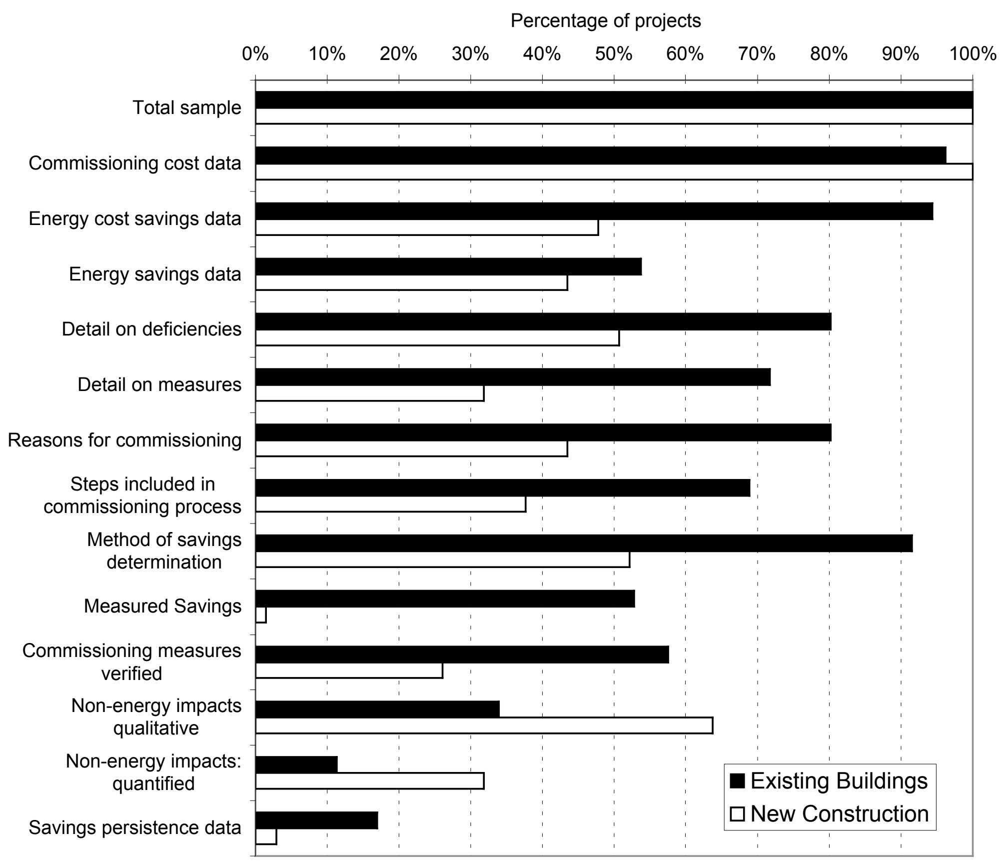


Table 5. Sample by building type and floor area.

	Total [ft^2]	Existing Buildings [ft^2]	New Construction [ft^2]
Education			
K-12	1,632,905	1,052,214	580,691
Higher education	2,724,358	2,405,178	319,180
Food Sales	127,401	-	127,401
Food Service	3,600	3,600	-
Health Care			
Inpatient	2,321,589	1,278,379	1,043,210
Outpatient	3,101,652	2,895,352	206,300
Laboratory	2,914,129	931,717	1,982,412
Lodging	786,138	637,116	149,022
Mercantile			
Retail	614,916	614,916	-
Service	227,000	227,000	-
Office	11,609,444	10,965,484	643,960
Public Assembly	1,104,433	397,210	707,223
Public Order and Safety	2,917,350	758,244	2,159,106
Religious Worship	-	-	-
Service	25,000	-	25,000
Warehouse and Storage	175,379	13,500	161,879
Other	127,380	67,380	60,000
Vacant	-	-	-
Total	**30,412,675**	**22,247,290**	**8,165,385**

Fig 6. Sample Depth



Key Findings

Table 6 and Figures 7 to 10 provide top-level findings for existing buildings and new construction, respectively, and Tables 7 and 8 provide more specific findings with min/max, median, average, and upper/lower quartile values. Our sample represents a total commissioning cost investment of about $17 million ($2003), for existing buildings and new construction

Table 6. Summary of results.

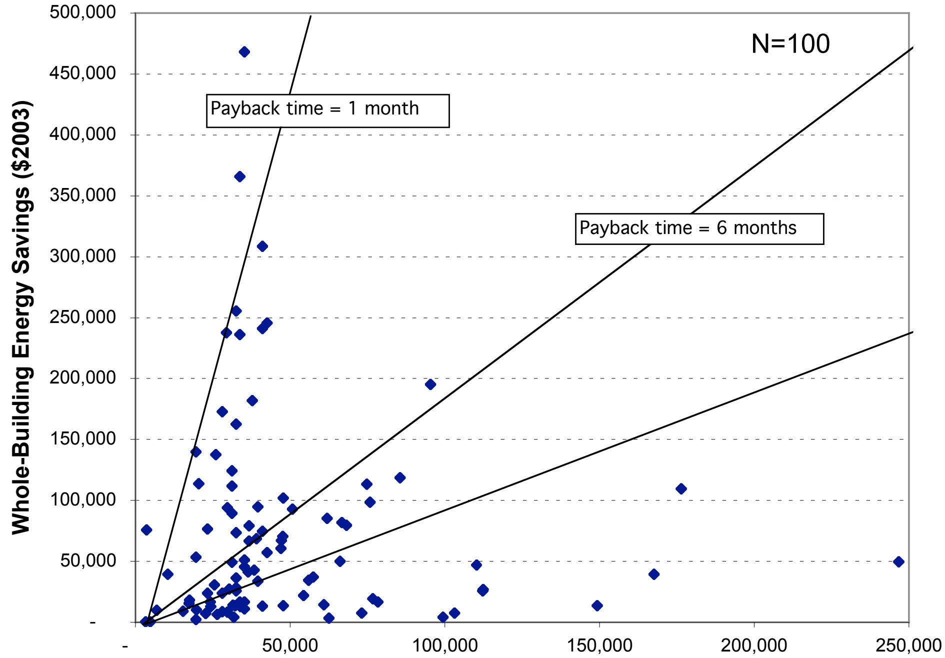
	All		Existing Buildings			New Construction		
	Total	Study sample size (Number of projects)	Total	Median per project	Study sample size	Total	Median per project	Study sample size
Number of projects	175	175	106		106	69		69
Number of buildings [1]	224	175	150	**1.4**	106	74	**1.1**	69
Number of states	21	175	15		106	15		69
Total project floor area (million ft^2)	30.4	175	22.2	**0.151**	106	8.2	**0.07**	69
Building age				**1978**	78		**1996**	59
Total new building construction costs ($million) [2]						1,514	**10.2**	58
Number of deficiencies identified	6,805	120	3,500	**11**	85	3,305	**26**	35
Commissioning cost as a fraction of total building construction cost (excluding non-energy benefits) [%]							**0.6%**	65
Total commissioning costs ($2003), excluding non-energy impacts [3]								
$1,000	16,984	171	5,223	**34**	102	11,760	**74**	69
$/ft2				**0.27**	102		**1.00**	69
Total Savings ($2003) [3]								
$1000/year[4]	8,840	133	8,022	**45**	100	818	**3**	33
$/ft2-year [4]				**0.27**	100		**0.05**	33
Whole-building energy cost savings (%)				**15%**	74			
Simple payback time, local energy prices [years]				**1.0**	99		**5.6**	38
Simple payback time: standardized US energy prices, including some cases with non-energy impacts [years] [5]				**0.7**	59		**4.8**	35

[1] Actual values likely higher. For the many data sources that did not specify number of buildings, we stipulated one.
[2] All costs in this table are in inflation-corrected 2003 dollars.
[3] Payback time should not be inferred from these two rows, as sample sizes are different.
[4] Total based on inflation-corrected local energy prices; median based on inflation-corrected standardized energy prices ($2003).
[5] A number of cases show commissioning costs partly or fully offset by resultant first-cost savings.

combined.[17] A catalog of summary information on the projects is provided in Appendix E.

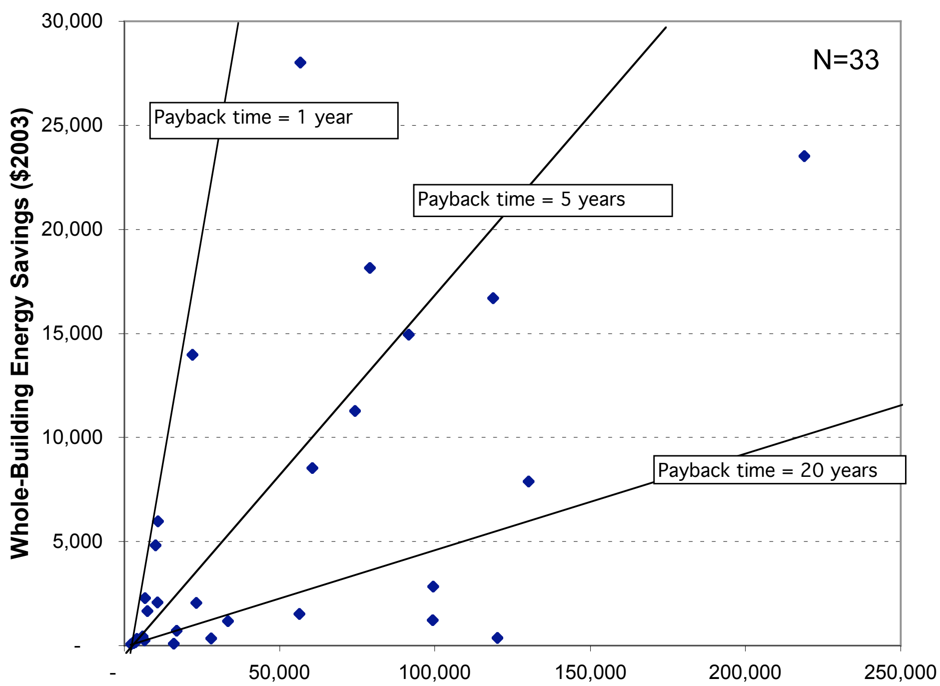
[17] . Unless otherwise noted, dollar values presented in the remainder of this report are normalized to year-2003 dollars, and savings calculations are only presented for projects with weather-normalized pre-/post-commissioning data.

Fig 7. Existing Buildings Commissioning: Costs, Savings, and Payback Times



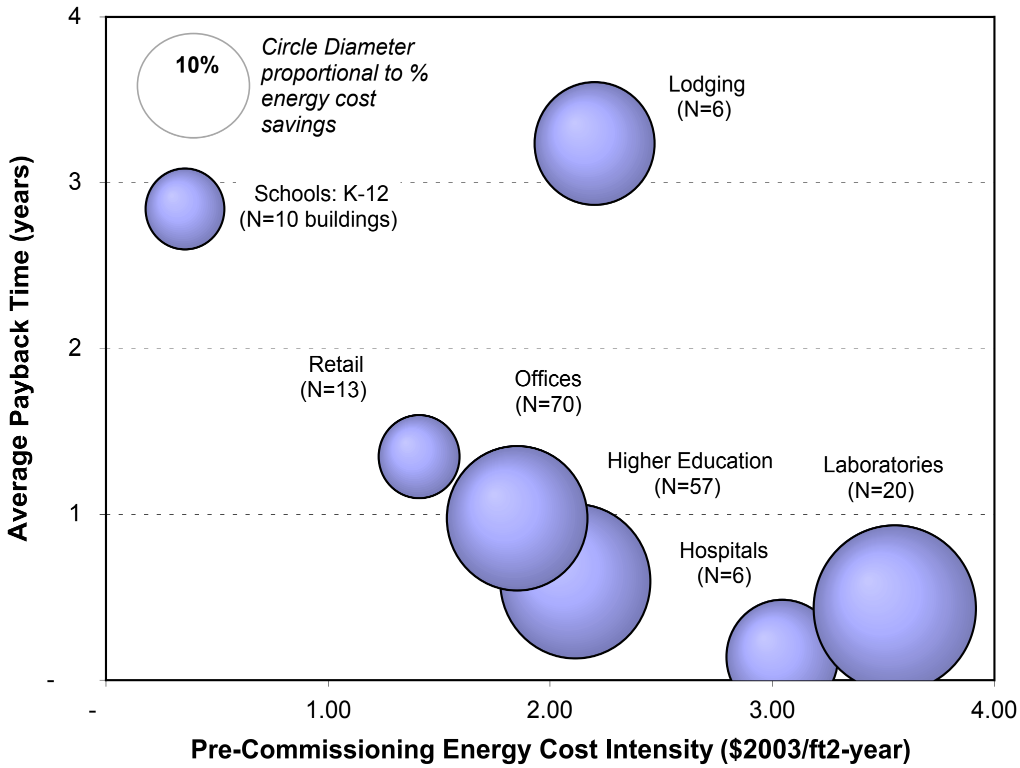
Outlier (35,184; 1,034,667)

Fig 8. New Construction Commissioning: Costs, Savings, and Payback Times



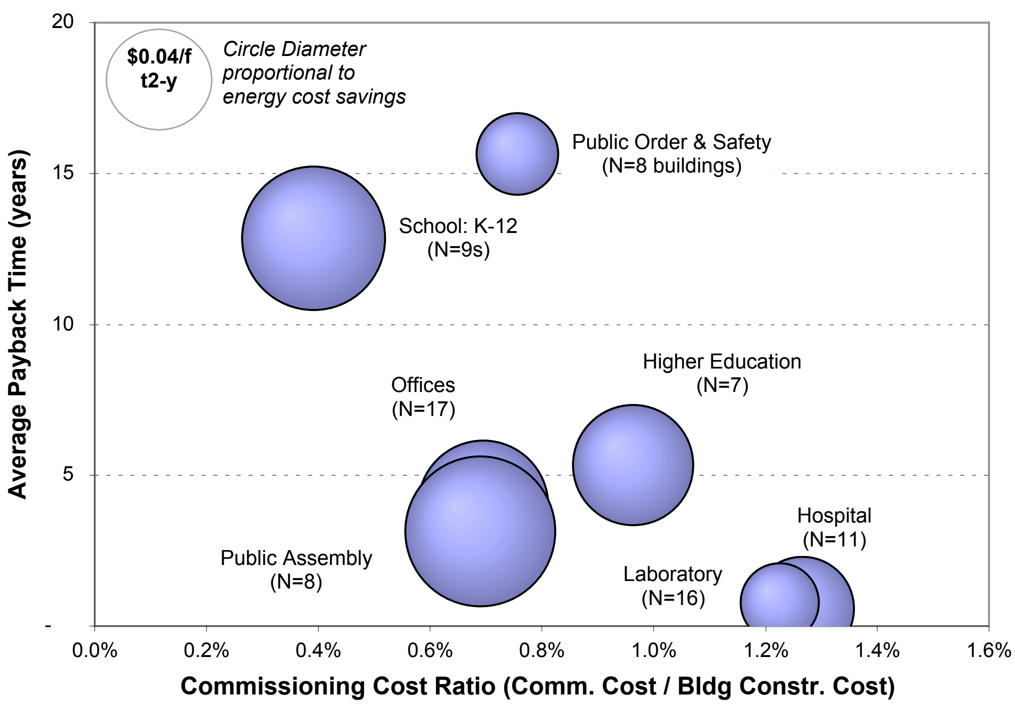
Outliers: (390,575;165,130), (661,752; 149,513), (1,126,000; 306,344)

Fig 9. Key Results by Building Type (Existing Buildings)



Excluding non-energy impacts

Fig 10. Key Results by Building Type (New Construction)



Excluding non-energy impacts

Table 7. Results summary with quartile analysis: Existing buildings.

	Units	Number of projects	Min	Bottom 25%	Median	Average	Top 25%	Max
Commissioned floor area	ft^2	106	5,690	95,101	**151,000**	209,729	271,650	1,014,133
Commissioning Costs								
Total	$2003/building	102	3,214	26,112	**33,696**	46,442	45,862	476,554
Normalized - excluding non-energy impacts, NEIs*	$\$2003/ft^2$	102	0.03	0.13	**0.27**	0.41	0.45	3.86
Normalized - only for cases including non-energy impacts, NEIs*	$\$2003/ft^2$	11	-0.27	0.04	**0.17**	0.41	0.45	1.88
Cx agent fee as percentage of total commissioning fee	%	9	32%	35%	**67%**	57%	71%	76%
Costs paid by:								
Building owner	%	31	0%	32%	**50%**	47%	50%	100%
Utility (e.g. as rebate)	%	48	20%	50%	**84%**	75%	100%	100%
Other (e.g. research grant)	%	7	33%	100%	**100%**	90%	100%	100%
Utility rebates (included in above costs)	$2003/building	48	917	11,932	**20,500**	23,685	25,000	76,725
as % of total costs	%	48	20%	50%	**84%**	75%	100%	100%
Deficiencies								
Per building	Number/building	85	0.7	5.0	**11**	32	21.0	640.0
Per 100kft2	$Number/100kft^2$	85	0.1	2.8	**6**	24	18.3	225.6
Measures								
Per building	Number/building	75	1.0	4.5	**9.0**	20.3	18.0	481.0
Per 100kft2	$Number/100kft^2$	66	0.1	2.5	**5.9**	8.6	12.7	218.6
Total Energy Cost Saving								
Raw data (mixed energy prices and years)	nominal $/building-yr	100	-25,752	11,739	**33,629**	66,489	75,940	879,101
Local energy prices	$2003/building-yr	100	-26,595	13,351	**37,376**	75,393	80,615	1,034,667
Standardized US-average energy prices	$2003/building-yr	57	-39,043	14,646	**44,629**	105,156	98,708	1,776,371
Percent energy bill savings	%	74	-3%	7%	**15%**	18%	28%	54%
Normalized Energy Cost Savings								
Raw data (mixed energy prices and years)	nominal $\$/ft^2$-yr	100	-0.09	0.11	**0.24**	0.42	0.46	3.83
Local energy prices	$\$2003/ft^2$-yr	100	-0.09	0.11	**0.27**	0.47	0.52	4.33
Standardized US-average energy price	$\$2003/ft^2$-yr	56	-0.13	0.11	**0.26**	0.54	0.72	3.23
Monetized non-energy Impacts (one-time)								
Per project	$2003/project (1000s)	10	-281	-31	**-17**	-45	-11	-1
Normalized by floor area	$2003/ft2-yr	10	-0.55	-0.45	**-0.18**	-0.26	-0.10	0.00
Energy Savings								
Electricity	kWh/ft^2-yr	57	-0.70	0.64	**1.7**	2.2	2.76	9.72
Percent savings	%	46	-5%	5%	**9%**	11%	15%	36%
Peak electrical power**	W/ft^2	6	0.1	0.4	**0.6**	0.7	0.8	1.6
Percent savings	%	3	1%	2%	**2%**	7%	9%	17%
Fuel	$kBTU/ft^2$-yr	29	-14.2	2.3	**6.5**	15.6	13.5	209.5
Percent savings	%	19	-16%	1%	**6%**	13%	23%	67%
Thermal (chilled water, hot water, steam)	$kBTU/ft^2$-yr	19	6	32	**64**	94	122	356
Percent savings	%	16	13%	23%	**36%**	37%	48%	63%
Total	$kBTU/ft^2$-yr	57	-15	7	**17.0**	49.3	56	357
Percent savings	%	46	-7%	7%	**15%**	19%	29%	57%
Payback Times [undiscounted]								
Raw data (mixed energy prices and years)	years	99	-1.5	0.4	**1.0**	2.1	2.0	20.7
Local energy prices and inflation-corrected cx costs	years	99	-1.5	0.3	**1.0**	2.1	2.4	26.1
Standardized U.S. energy prices and inflation-corrected cx costs	years	59	-1.0	0.2	**0.7**	1.7	2.1	10.4

* Non-energy impacts (NEIs) include increases or decreases in first or operating costs due to changes in maintenance costs, contractor callbacks, equipment life, and
** Most are averaged over the entire year, hence true "peak" savings are significantly higher than shown here.

Table 8. Results summary with quartile analysis: New construction.

		Number of projects	Min	Bottom 25%	Median	Average	Top 25%	Max
Commissioned floor area	ft^2	69	1,072	32,268	**69,500**	118,369	151,000	685,000
Commissioning Costs								
Total	\$2003/building	69	2,089	19,515	**74,267**	165,139	218,960	1,126,000
Normalized - excluding non-energy impacts, NEIs*	\$2003/ft^2	69	0.10	0.49	**1.00**	1.64	1.66	18.20
Normalized - only for cases including non-energy impacts, NEIs*	\$2003/ft^2	22	-7.82	-0.27	**0.35**	0.11	1.22	4.40
As % of construction cost (excl. NEIs) [%]*	%	65	0.1%	0.3%	**0.6%**	0.9%	1.1%	5.9%
As % of construction cost (incl. NEIs) [%]*	%	22	-5.2%	-0.2%	**0.2%**	0.03%	0.8%	1.5%
Cx agent fee as percentage of total commissioning fee	%	25	56%	74%	**80%**	78%	86%	94%
Costs paid by:								
Building owner	%	23	50%	50%	**50%**	72%	100%	100%
Utility (e.g. as rebate)	%	31	50%	50%	**100%**	79%	100%	100%
Other (e.g. research grant)	%	2	-	-	**-**	-	-	-
Utility rebates (included in above costs)	\$2003/building	31	2,089	6,542	**16,650**	27,055	42,677	128,265
as % of total costs	%	31	50%	50%	**100%**	79%	100%	100%
Deficiencies								
Per building	Number/building	34	2	4	**28**	67	75	705
Per 100kft2	Number/100kft^2	34	5	16	**37**	90	81	1,010
Measures								
Per building	Number/building	21	2	3	**7**	55	30	705
Per 100kft2	Number/100kft^2	22	5	13	**20**	13	43	285
Total Energy Cost Saving								
Raw data (mixed energy prices and years)	nominal \$/building-yr	33	39	352	**1,944**	22,604	14,628	300,000
Local energy prices	\$2003/building-yr	33	46	359	**2,288**	24,785	14,937	306,344
Standardized US-average energy prices	\$2003/building-yr	27	-88	622	**2,533**	9,226	13,722	61,288
Percent energy bill savings	%	3	-	-	**-**	-	-	-
Normalized Energy Cost Savings								
Raw data (mixed energy prices and years)	nominal \$/ft^2-yr	33	0.00	0.02	**0.05**	0.25	0.13	3.20
Local energy prices	\$2003/ft^2-yr	33	0.00	0.02	**0.05**	0.29	0.16	3.84
Standardized US-average energy price	\$2003/ft^2-yr	30	0.00	0.02	**0.05**	0.11	0.19	0.44
Monetized non-energy Impacts								
Per project	\$2003/project (1000s)	22	-1418	-138	**-51**	-177	-15	17
Normalized by floor area	\$2003/ft2-yr	22	-43.93	-6.96	**-1.24**	-6.11	-0.23	0.43
Energy Savings								
Electricity	kWh/ft^2-yr	29	-0.49	0.20	**0.5**	1.2	1.36	5.63
Percent savings	%	3	-	-	**-**	-	-	-
Peak electrical power**	W/ft^2	11	0.0	0.03	**0.1**	0.2	0.2	0.6
Percent savings	%	-	-	-	**-**	-	-	-
Fuel	kBTU/ft^2-yr	18	-3.6	0.2	**2.2**	2.1	3.4	13.5
Percent savings	%	0	-	-	**-**	-	-	-
Thermal (chilled water, hot water, steam)	kBTU/ft^2-yr	0	-	-	**-**	-	-	-
Percent savings	%	0	-	-	**-**	-	-	-
Total	kBTU/ft^2-yr	30	-1	2	**3.2**	6.2	8	26
Percent savings	%		-	-	**-**	-	-	-
Payback Times [undiscounted]								
Raw data (mixed energy prices and years)	years	39	0.0	1.9	**6.5**	23.0	19.5	303.1
Local energy prices and inflation-corrected cx costs	years	38	0.0	1.9	**5.6**	21.9	22.6	175.4
Standardized U.S. energy prices and inflation-corrected cx costs	years	35	0.0	1.2	**4.8**	14.0	16.6	105.0

* Non-energy impacts (NEIs) include increases or decreases in first or operating costs due to changes in maintenance costs, contractor callbacks, equipment life, and

** Most are averaged over the entire year, hence true "peak" savings are significantly higher than shown here.

Existing Buildings

Drivers, Scope, and Expenditures

Our compilation includes existing-buildings commissioning results for 150 existing buildings (106 projects), representing 22.2 million square feet of floor space. The median building size was 151,000 square feet and the median year constructed was 1978.

The 85 cases providing information on reasons for commissioning reported a wide range of drivers, the most important being energy savings (94%), with more general performance considerations, thermal comfort, occupant productivity, and ensuring indoor air quality also ranking high (Figure 11).

The scope of commissioning varied from project to project. Figure 12 presents our characterization of fifteen distinct steps in the process (for 73 reporting projects), and indicates the share that included each given step. No one project included every step, although most developed a formal commissioning plan, performed trend analysis, estimated cost savings, and implemented operations and maintenance improvements.

The total investment in existing-buildings commissioning (in inflation-corrected 2003 dollars) was \$5.2 million with a median value of about \$33,696 per project (\$46,442 average; N=102 projects), or \$0.27 per square foot (range of \$0.13 to \$0.45 from the first to third quartiles). The full range of costs was much wider, from a minimum value of \$0.03 to \$3.86 per square foot. For the subset (11 projects) with quantified non-energy impacts, the median cost was \$0.17 per square foot (with an inter-quartile range of \$0.04 to \$0.45 per square foot). Commissioning agent fees ranged from 35 percent to 71 percent (first to third quartiles) of total commissioning costs, with a median value of 67 percent (with 9 projects reporting this information).

For the 55 projects reporting, the primary usage of commissioning funds was for investigation and planning (69 percent), followed by actual implementation of measures (27 percent), with reporting and the verification and persistence tracking had important but more minor roles (Figure 13). Building owners, utilities, and other third parties (e.g., government grants) have all played important roles in funding and co-funding commissioning projects (details in Table 7). In the 48 projects reporting utility funding, the median contribution by utilities was 84 percent of total costs commissioning costs, corresponding to a median incentive of \$20,500 per project.

For existing buildings, normalized commissioning costs expectedly scaled downwards with floor area, dropping considerably for buildings above 200,000 square feet. Possible reasons for this will be discussed below.

Fig 11. Reasons for Existing Buildings Commissioning (N=85)

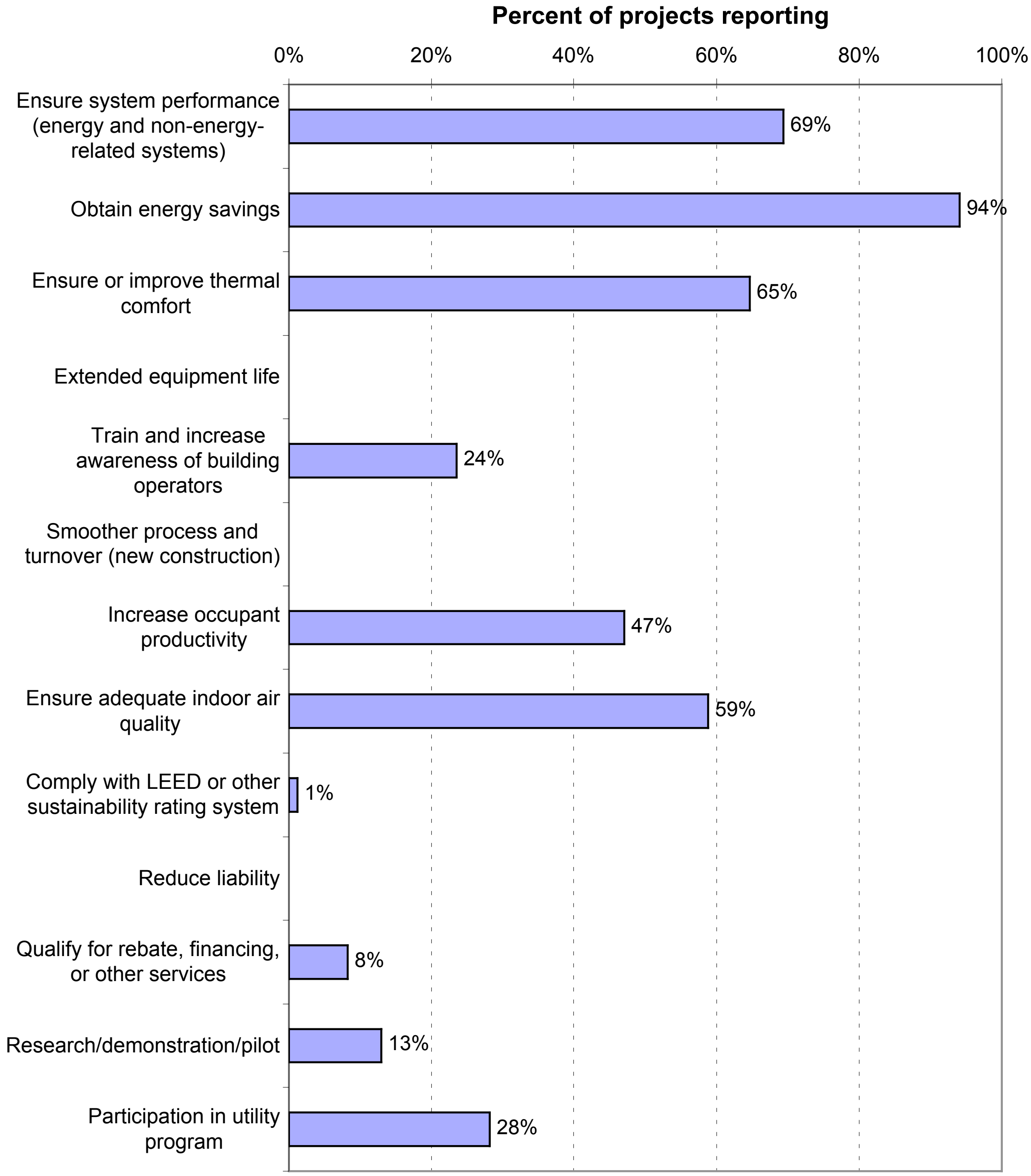


Fig 12. Scope of Existing Buildings Commissioning (N=73)

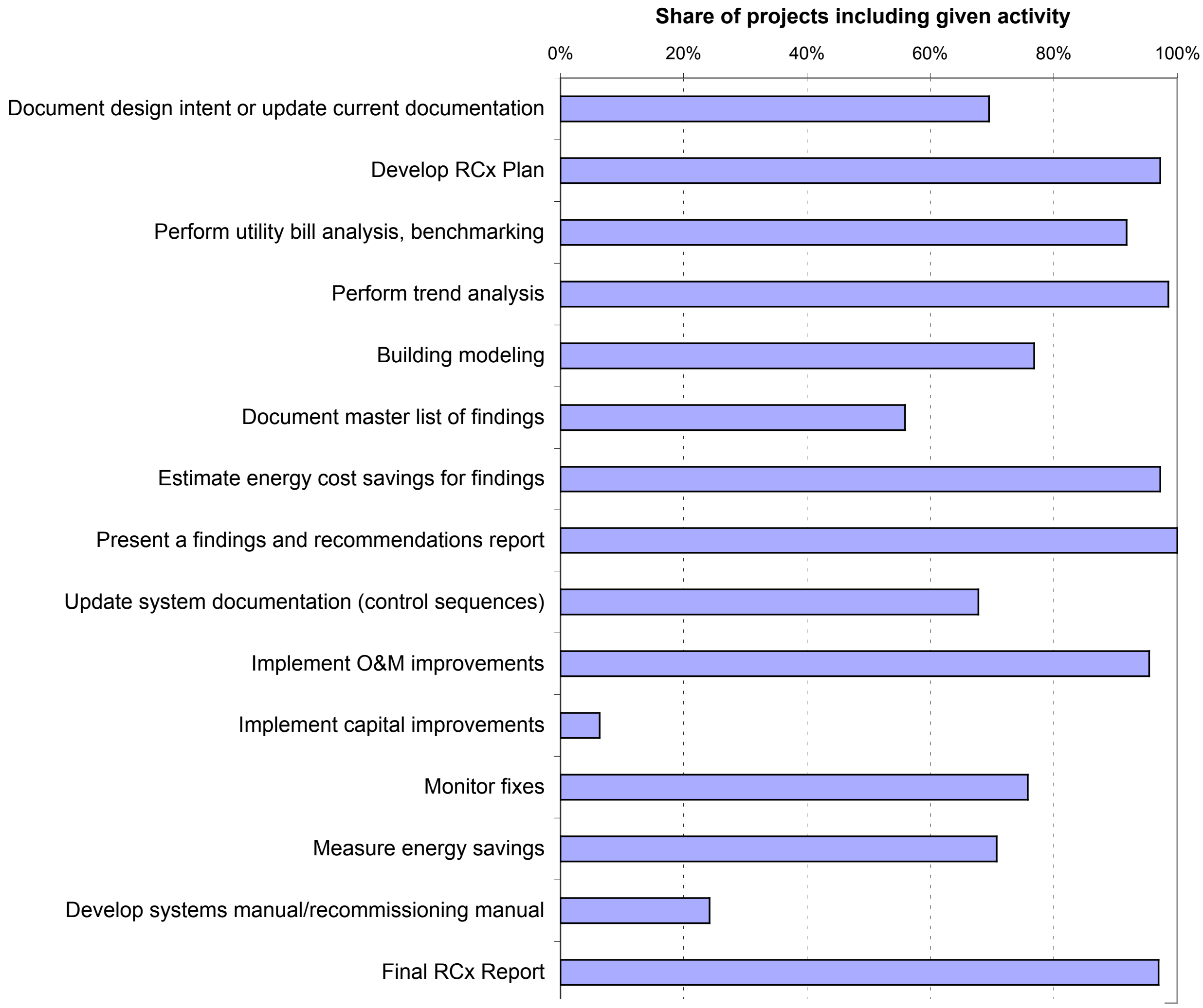
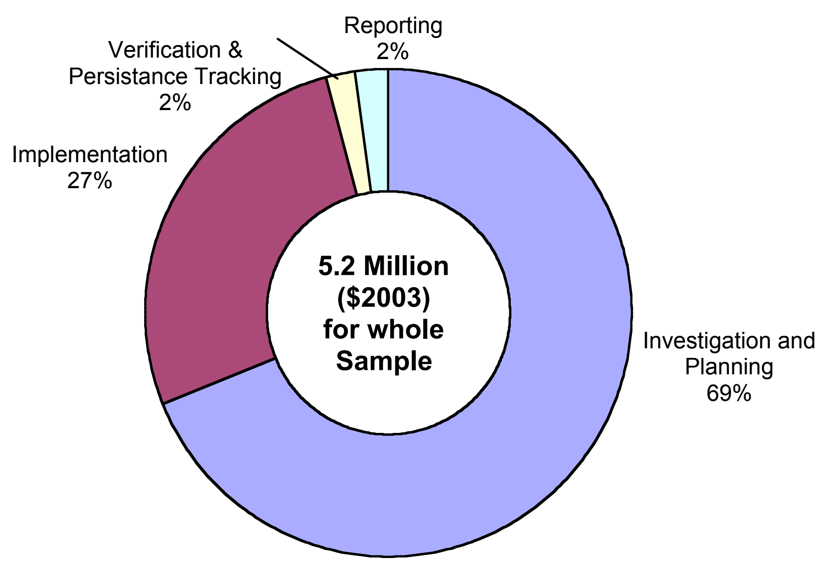


Fig 13. Commissioning Cost Allocation (Existing Buildings, N=55)



Impacts

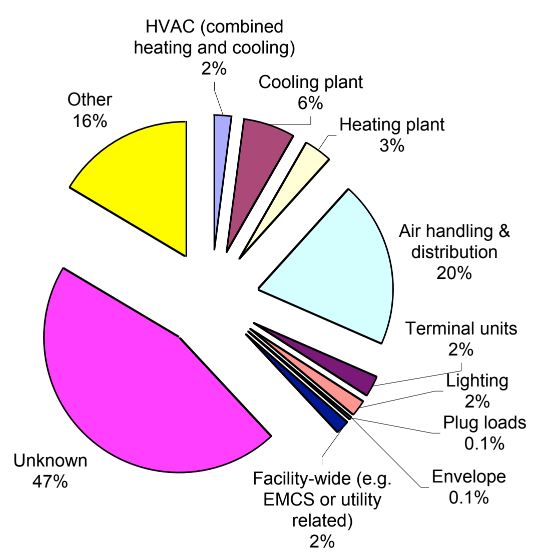
We find that investments in existing-buildings commissioning have yielded considerably positive results, as outlined below.

Deficiencies and measures

Among the 85 studies reporting, 3500 deficiencies were found in the process of existing-buildings commissioning, with a median value of 11 deficiencies per building (ranging as high as 640). Problems with air-handling and distribution were the most prevalent, followed by cooling and then heating plant (Figure 14). A significant proportion of the total were not characterized.

The number of corresponding measures was somewhat lower, although counting conventions make it difficult to compare the two datasets, and there is not necessarily a one-to-one correspondence between the number of deficiencies and measures (Figure 15). The leading measure within the Design, Installation, Retrofit, Replacement category involved some form of equipment retrofit/replacement (e.g., replacing faulty sensors) (216 cases). Within the Operations and Control category, the leading measure was implementing advanced reset (131 cases), and within the Maintenance category, the leading measure was mechanical fixes (147 cases), closely followed by calibration (114 cases).

Fig 14. Number of Deficiencies Identified by Building System (Existing Buildings, N = 3,500)



We compiled Measures Matrices for 69 of the existing-buildings projects analyzed in this study. These matrices show the correspondence between the building component or system in which a deficiency was found and the type of measure implemented. Approximately 700 measures were mapped against their corresponding deficiencies (Table 9). Again, the greatest prevalence of measures is seen in air handling and distribution systems, 357 in all (followed by cooling plant), with implementation of advanced reset the most popular measure. Other particularly frequent measures include modification of set-points, scheduling, and control sequences; calibration; mechanical fixes; and equipment replacements. The overall category of "Operations and Control" is clearly the epicenter of commissioning measure implementation. The small number of measures in the "Other" categories suggests that the matrix adequately accommodates the types of issues that arise in existing buildings. In our judgment, the virtual absence of measures in building envelopes and plug loads (and perhaps lighting) is probably more reflective of a lack of inspection in these areas than the actual absence of deficiencies.

Fig 15. Frequency of Recommended Measures (Existing Buildings, N=1606)

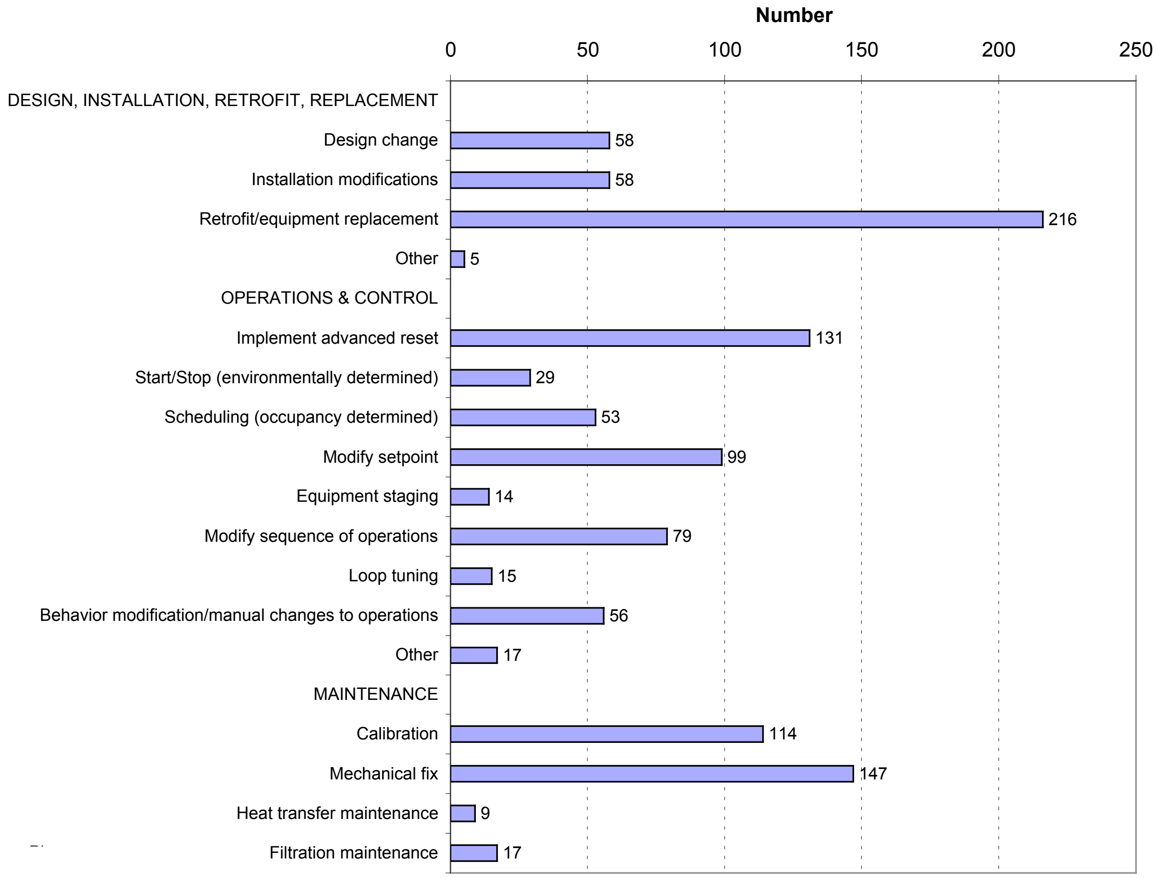


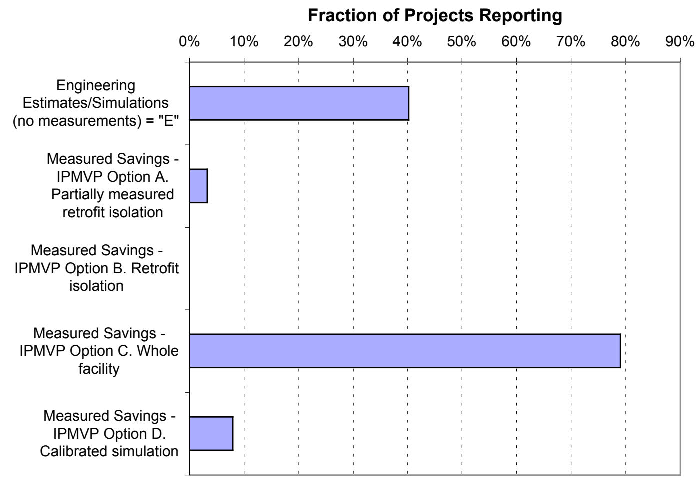
Table 9. Results from Measures Matrices: Existing buildings (69 projects) [yellow highlights indicate most common measures, deficiencies, and combinations].

		Design, Installation, Retrofit, Replacement				Operations & Control									Maintenance						
N (paired) = 702		Design change	Installation modifications	Retrofit/equipment replacement	Other	Implement advanced reset	Start/Stop (environmentally determined)	Scheduling (occupancy determined)	Modify setpoint	Equipment staging	Modify sequence of operations	Loop tuning	Behavior modification/manual changes to operations	Other	Calibration	Mechanical fix	Heat transfer maintenance	Filtration maintenance	Other	Deficiency unmatched to specific measure	Total
Deficiencies		D1	D2	D3	D4	OC1	OC2	OC3	OC4	OC5	OC6	OC7	OC8	OC9	M1	M2	M3	M4	M5		
HVAC (combined heating and cooling)	V	0	2	8	1	1	1	5	3	1	5	0	0	2	5	7	1	5	2	12	61
Cooling plant	C	4	11	19	0	26	5	4	10	4	27	3	12	2	4	10	1	0	0	13	155
Heating plant	H	4	0	5	0	15	7	1	4	0	7	1	5	1	4	7	1	0	0	18	80
Air handling & distribution	A	15	9	19	3	80	9	21	25	4	24	12	14	6	40	27	3	4	2	40	357
Terminal units	T	1	3	2	1	4	0	3	14	0	4	1	2	1	7	10	0	0	0	8	61
Lighting	L	3	1	17	1	1	2	4	0	0	0	0	5	0	2	1	0	0	0	1	38
Envelope	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plug loads	P	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Facility-wide (e.g. EMCS or utility related)	F	2	3	2	0	1	0	7	0	0	1	1	7	2	2	2	1	0	0	3	34
Other	O	0	0	2	0	0	0	0	2	0	1	0	1	0	0	3	0	0	1	12	22
Deficiency unmatched to specific measure		10	9	7	0	2	2	1	29	2	7	2	4	1	12	10	0	0	0		**809**
Total		39	38	81	6	130	26	46	87	11	76	20	51	15	76	77	7	9	5	**800**	

Energy savings and cost-effectiveness

The underlying energy data represent a mix of measured and engineering estimates. Approximately 40% of the cases were based strictly on estimates, while the balance involved some degree of measurement (often in combination with estimation methods). We describe the type of measurement, using the terms of the International Performance Measurement and Verification Protocols (Appendix D), as show in Figure 16. Whole-facility measurement (master-metering) was by far the most common, although sub-metering or calibrated simulation were used in some cases.

Fig 16. Commissioning Savings Verification Methods (Existing Buildings, N=97)



Amounts total more than 100% because more than one method used in some cases

Figures 17 to 23 provide a variety of vantage points on the cost-effectiveness analysis for existing-buildings commissioning. Only one project experienced an overall increase in energy use, which could result, for example, from fixing a broken (non-operating) piece of equipment. Most projects achieved energy savings in each form of energy targeted by commissioning (95 percent of projects achieved electricity savings, 79 percent in the case of gas, and 100 percent in the case of purchased thermal energy). Median total (whole-building) savings were 17 kBTU/ft^2-year (15%) [and 1.7 kWh/ft^2-year (9%) for electricity, 0.6 W/ft2 for peak electric power (2%), 6.5 kBTU/ft^2-year (6%) for natural gas, and 64 kBTU/ft^2-year for purchased thermal energy (36 percent, e.g., metered hot water]. These include a mix of projects for which commissioning ranged from limited (e.g., to a particular energy efficiency measure) to comprehensive (whole-building). The upper quartile of total energy savings was significantly higher in each case (Tables 7 and 8). In individual cases, savings ranged to over 50 percent of whole-building energy use.

Notably, the cost-effectiveness of existing-buildings commissioning projects using measured data (N=55) was significantly higher than for those relying only on engineering estimates (N=35): \$0.58/ft^2-year energy bill savings (0.4 year payback time) versus \$0.22/ft^2-year (1.3 year payback time). Possible explanations include that savings measurement correlated with greater care in the commissioning process generally—and revealed additional deficiencies that were in turn corrected—or that estimates were conservative by design. However, the cohort with measured savings contained more energy-intensive buildings, most of which were located in Texas. The observations are thus inconclusive.

Median standardized annual energy cost savings were \$44,629 per building (average 105,156 per building, N = 100 projects). Median normalized energy cost savings were \$0.26/ft^2-year. Savings ranged as high as \$1.8 million per building per year (\$3.83/ft^2-year). Savings approached or exceeded 50 percent of whole-building energy costs in a number of cases (Figure 17).

Notably, energy cost savings, energy savings, and corresponding payback times did not correlate strongly with pre-commissioning energy intensity (Figure 19), indicating that commissioning of "ordinary" or even "efficient" existing buildings can be effective, while payback times declined with increasing building size, especially for buildings with floor area above 100,000 square feet. This is shown in Figure 18, which also provides an opportunity to see the effect of normalizing raw data to standardized energy prices and correcting for inflation.

Almost every project was highly cost effective. Median payback times of 1 year (N=99 projects) were achieved based on the raw data (un-normalized for energy prices or inflation), dropping to 0.7 years (N=59) when data were normalized to standardized average U.S. energy prices and commissioning costs are inflation-corrected (all in $2003). Upper-quartile paybacks were approximately 2 years, and 0.2 years for the lower quartile. While, on average, normalization for energy prices and inflation did not have a large absolute effect, adjusted values varied by up to a factor of four in individual cases.

Fig 17. Energy Cost Savings: Existing Buildings (median savings 15%; average savings 18%)

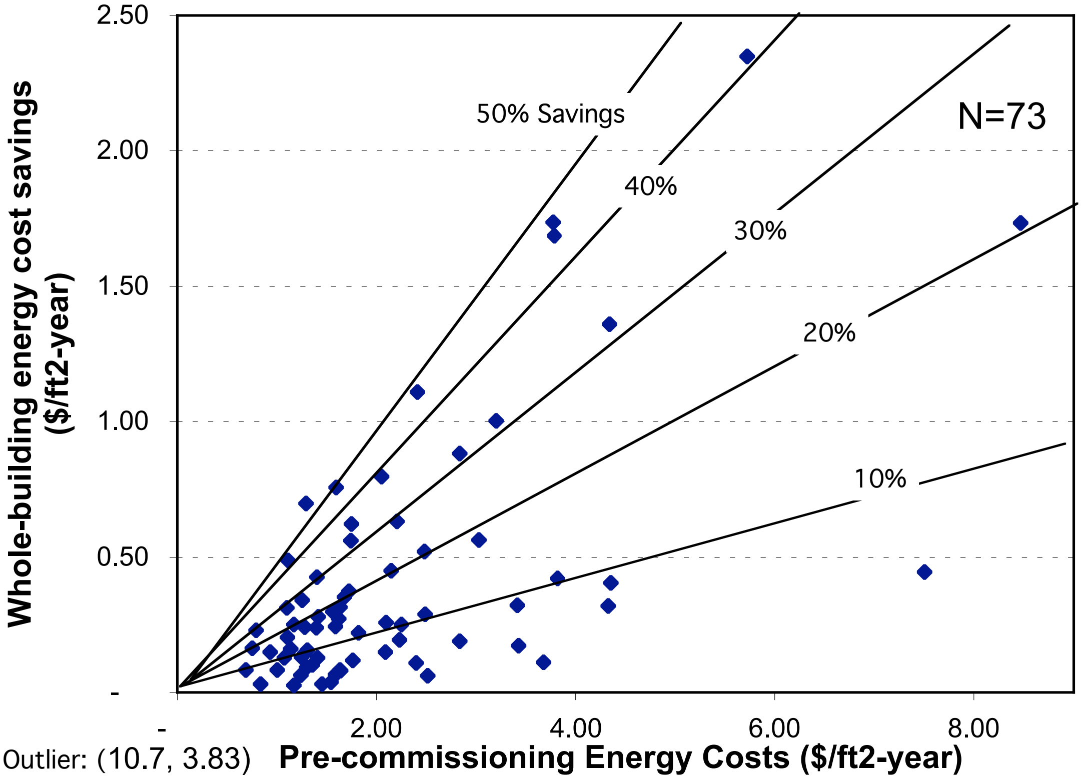


Fig 18. Commissioning Payback Time vs. Building Size (Existing Buildings)

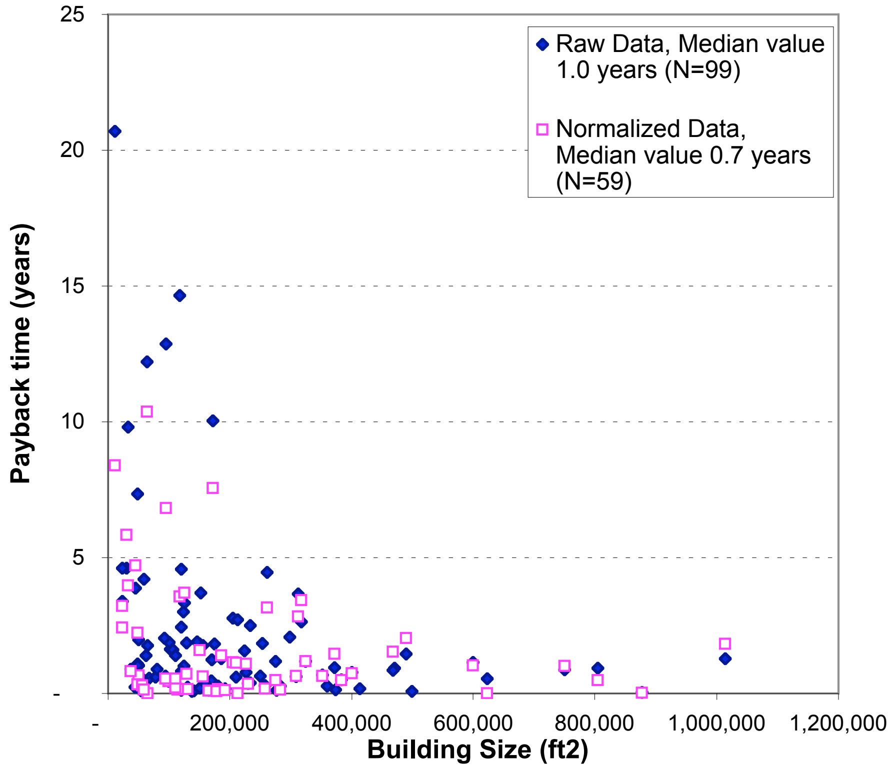


Fig 19. Payback Time versus Pre-Retro-Commissioning EUI (Existing Buildings)

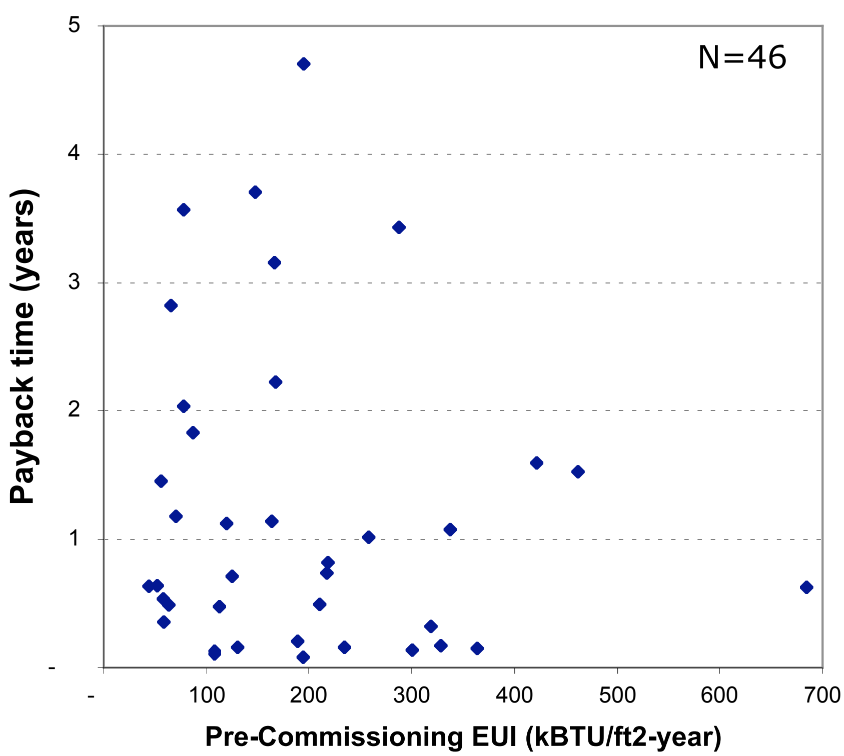


Fig 20. Electricity Savings as a Function of Pre-Commissioning Intensities (Existing Buildings)

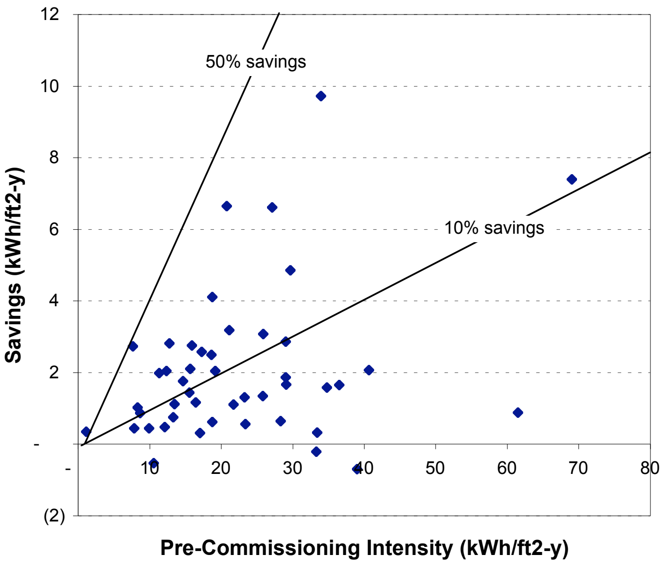
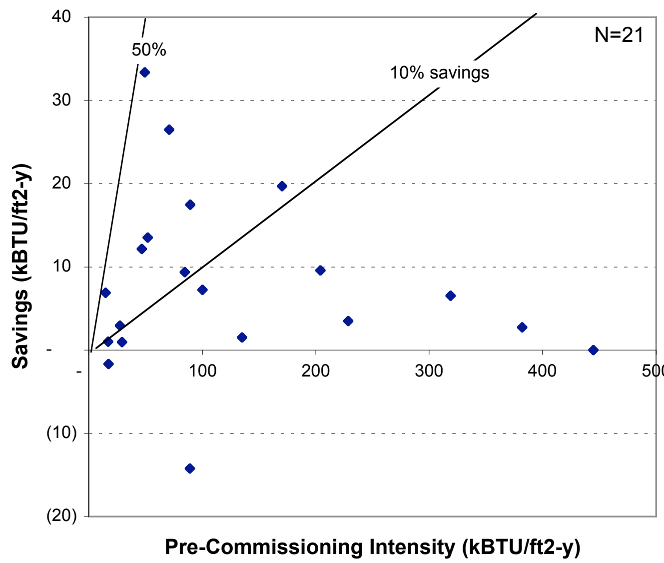


Fig 21. Natural Gas Savings as a Function of Pre-Commissioning Intensities (Existing Buildings)



Outlier: (551, 209)

Fig 22. Purchased Thermal Energy Savings as a Function of Pre-Commissioning Intensities (Existing Buildings)

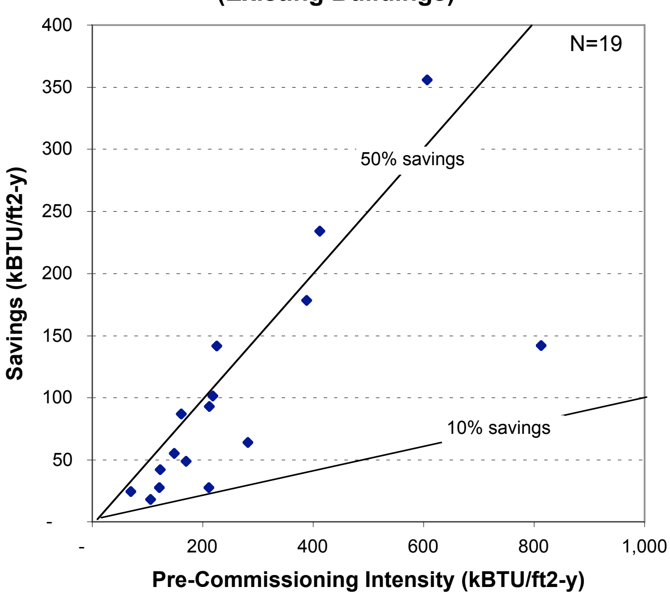
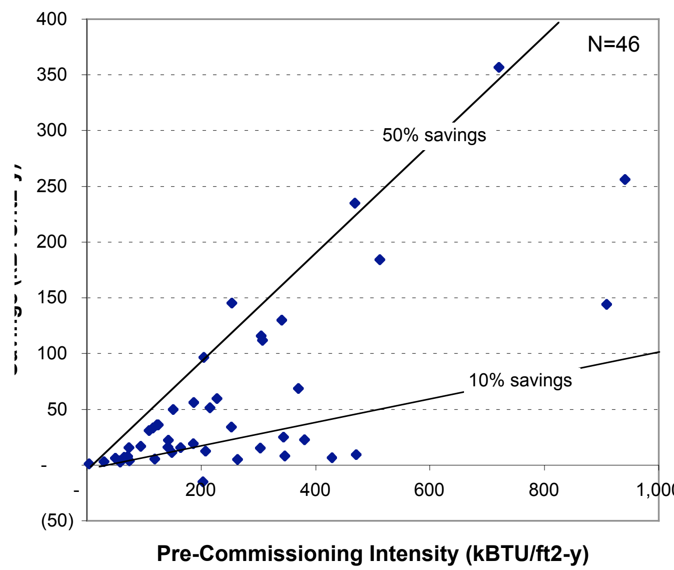


Fig 23. Total Energy Savings as a Function of Pre-Commissioning Intensities (Existing Buildings)



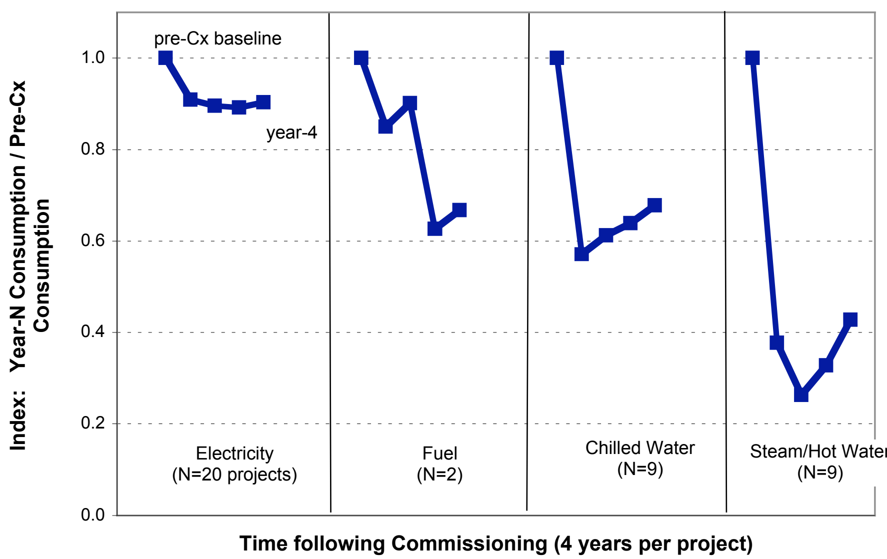
Formation and persistence of savings

For the cases where multi-year data were available on energy use and savings trends, it is clear that that savings can manifest gradually and thus one may underestimate savings if using data only from the first post-commissioning year. This caveat is applicable in cases where the commissioning agent makes recommendations that are only subsequently (and potentially gradually) implemented by in-house personnel.

On the other hand, savings are also not permanent, and can erode as the building falls back into disrepair or otherwise "out of tune." Similarly, the measure life can also be quite finite (e.g., when replacing a fouled filter). Figure 24 illustrates these effects for 20 projects over a four-year period. Electricity savings were both most shallow and most likely to persist, while those for steam or hot water were deepest, but least likely to persist. Payback times were shorter than the period over which savings are observed to erode.

Only two formal studies have been conducted on the persistence of existing building commissioning, for a total of 18 existing buildings (Turner *et al.* 2001; Bourassa *et al.* 2004). Those results are included in our compilation. Repeated or follow-up commissioning of existing buildings is likely to be indicated when consumption increases significantly. This was necessary in two buildings of a ten building study within four years (Claridge *et al.*, 2002).

Fig 24. Emergence & Persistence of Energy Savings (weather-normalized)

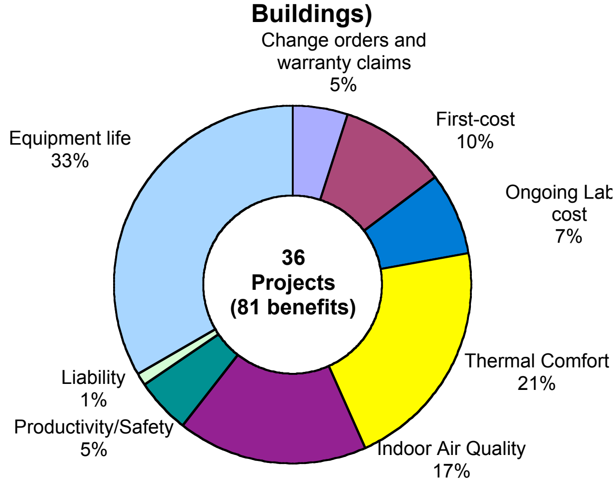


For the ten cases provided by the Energy Systems Laboratory at Texas A&M University, almost 75% of the increase in energy use was caused by significant component failures and/or control changes (related to other building problems) that did not compromise comfort, but caused large changes in consumption. The remainder (25% of the observed increase) was due to control changes implemented by the operators. This suggests that tracking consumption for evidence of significant consumption increases is the most important indicator of a need for follow-up commissioning. It also suggests that hidden component failures are a major (possibly *the* major) culprit in persistence problems.

Non-energy impacts

Of the existing projects in this compilation, information on 81 perceived non-energy benefits was available for 36 cases. Extended equipment lifetime was reported in one-third of the cases, and improved thermal comfort in one-fifth of the cases (Figure 25). Other benefits, in order of decreasing incidence, involved indoor air quality, first-cost reductions, labor savings, productivity/safety, change orders and warranty claims, and liability reduction. Where the economic value of these impacts (10 cases) was quantified (median value of -$17,000 per project – negative value corresponds to savings, positive value to increased cost), we included it in the cost-benefit analysis. The median NEI value was -$0.18/ft^2 with an inter-quartile range of -$0.10 to -$0.45/ft^2.

Fig 25. Reported Non-Energy Impacts (Existing Buildings)



New Construction

Drivers, Scope, and Expenditures

Our compilation includes commissioning results for 69 new-construction projects (74 buildings), representing 8.2 million square feet of floor space. The median building size was 69,500 square feet and the median year constructed was 1996. The total construction value of these buildings exceeded $1.5 billion ($2003).

The 30 cases providing information on reasons for commissioning reported a wide range of drivers, the most important of which was ensuring system performance (87%), with ensuring comfort, indoor air quality, operator training, and energy savings also ranking high (Figure 26).

The scope of new-construction commissioning varied from project to project. Figure 27 presents our characterization of sixteen distinct steps in the process (for 26 reporting projects), and indicates the share of projects that included each step. No one project included every step. Most projects included developing a written commissioning specifications and preparing a formal commissioning plan, verification checks, functional testing, training, and review of O&M manuals.

The total investment in new-construction commissioning (in inflation-corrected 2003 dollars) was $11.8 million with a median value of $74,000 per project (N=69 projects), or $1.00 per square foot (an inter-quartile range of $0.49 to $1.66 from the first to third quartiles). The full range of costs was much wider, from a minimum value of $0.10 to $18.20 per square foot. Commissioning agent fees ranged from 74 percent to 86 percent of the total commissioning investment (first to third quartiles), with a median value of 80 percent (with 25 projects reporting this information).

Energy savings are more difficult to quantify than is the case for existing buildings because there is no actual pre-commissioned building to measure. Instead, engineering calculations or simulations are used to estimate savings. As many of the new-construction projects emphasized a small number of measures, rather than a whole-building effort, many of the savings are small – the median value is $2,533 per year ($0.05/ft^2-year). The average value is much higher at $9,226 ($0.11/ft^2-year), because the relatively small number of comprehensively commissioned cases have a greater weight. When local energy prices are used, average savings rise to approximately $25,000 per year (because the local prices for this cohort tend to be significantly higher than the national-average value used in deriving our normalized estimates).

Fig 26. Reasons for New-construction Commissioning (N=30)

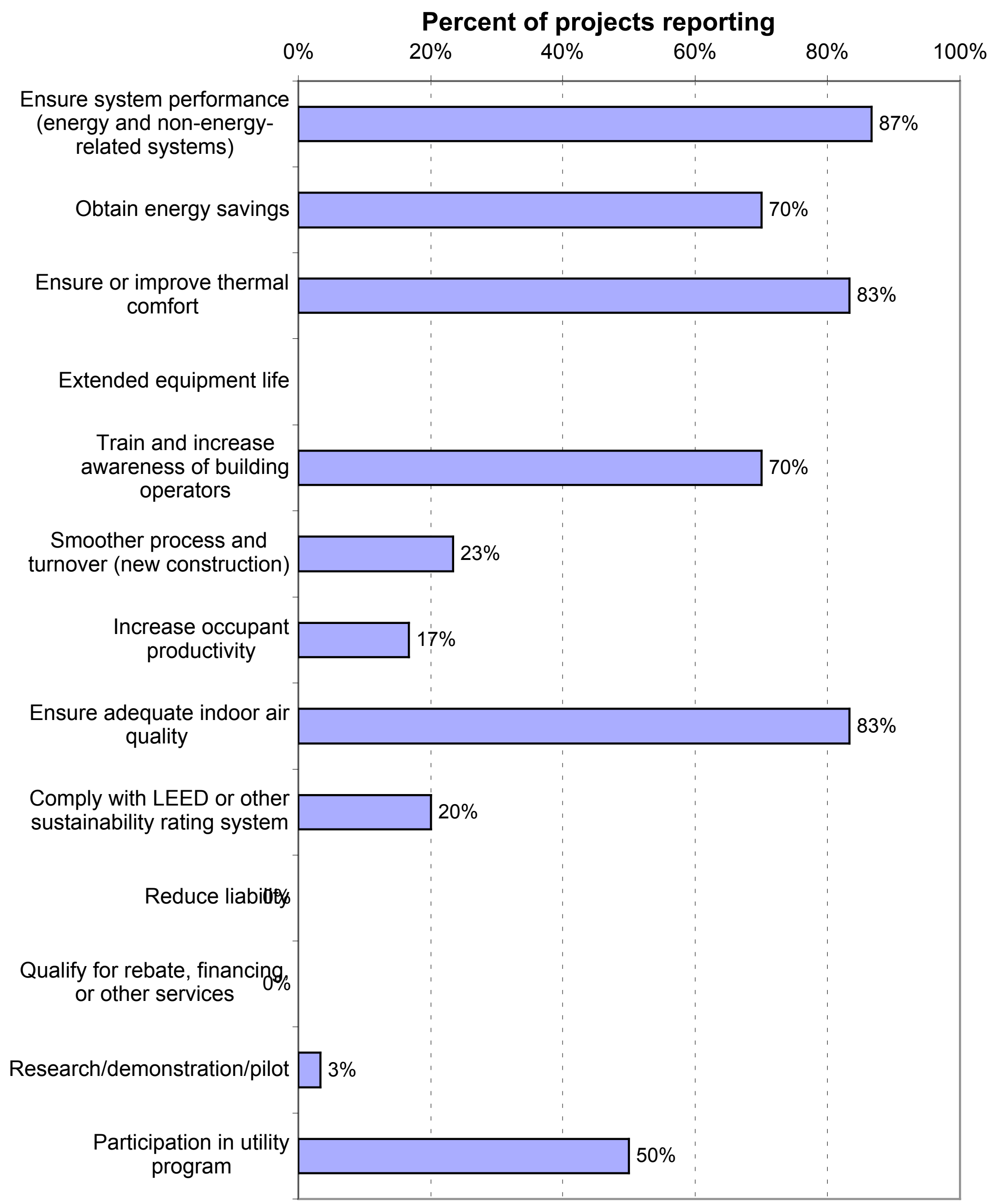


Fig 27. Scope of New-Construction Commissioning (N=26)

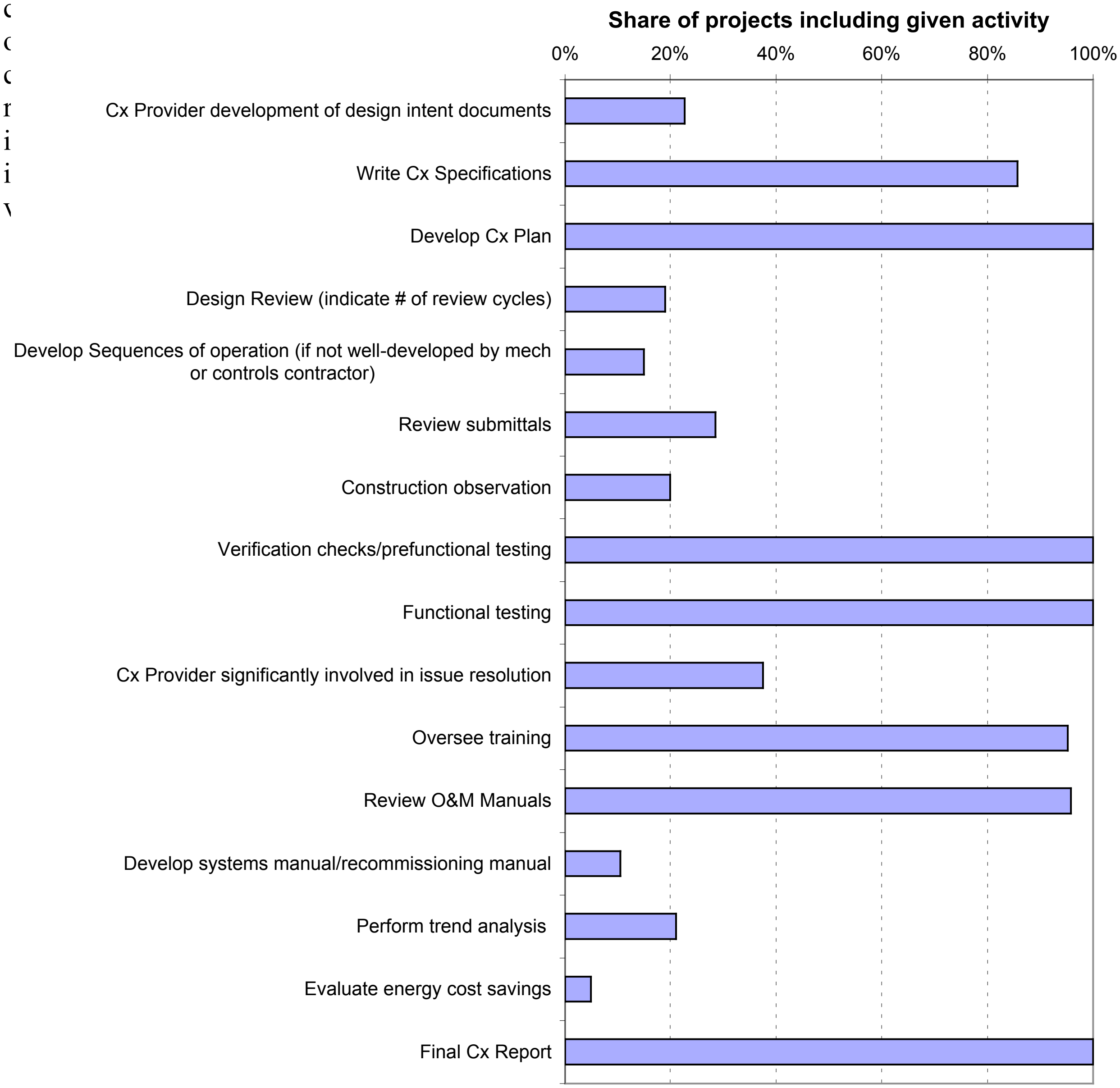
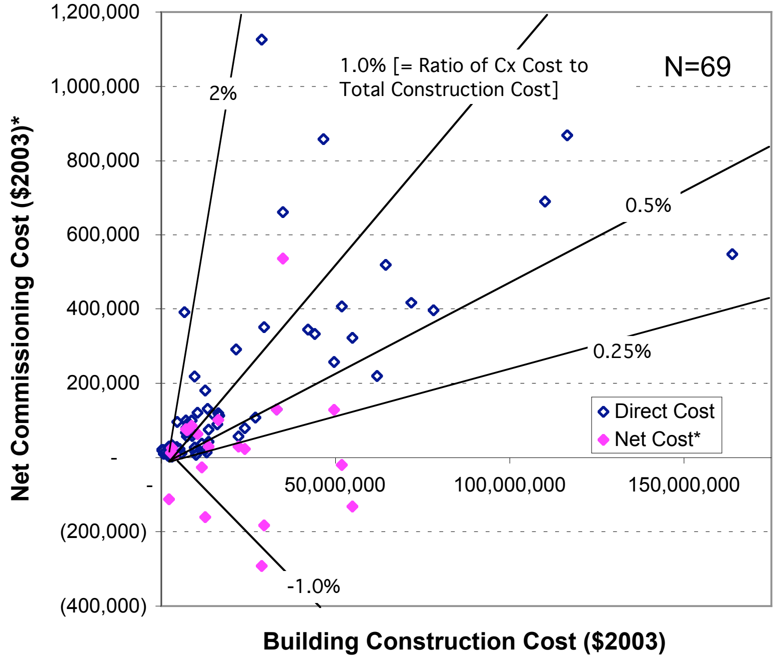
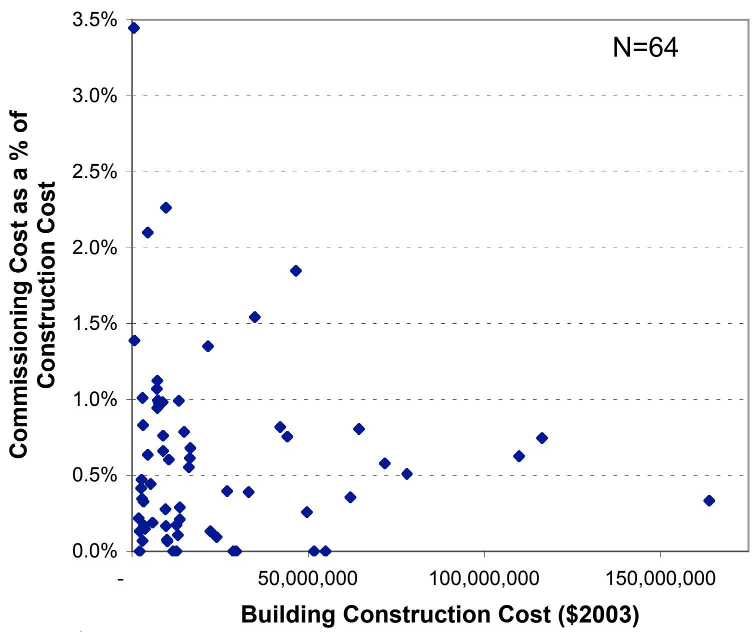


Fig 28. Commissioning Cost vs. Project Cost (New Construction)



Includes first-cost savings resulting from commissioning

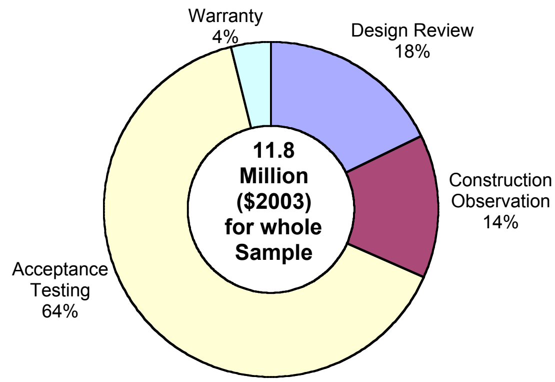
Fig 29. Commissioning Cost Ratio vs. Construction Cost (New Construction, excuding NEIs)



Outlier: ($6.7M, 5.9%)

For the 5 projects reporting, the primary usage of commissioning funds was for acceptance testing (64%), followed by design review (18%), with construction observation and warranty making up the balance (Figure 30). Building owners, utilities, and other third parties (e.g., government agencies) have all played important roles in funding and co-funding the new-construction commissioning projects. Utility rebates were widely used, with a median value of $16,650 across the 31 reporting projects.

Fig 30. Commissioning Cost Allocation (New Construction, N=5)



For new construction, normalized commissioning costs did not scale downwards with increasing floor area, suggesting that the fixed cost is lower than the variable cost. This is a notable difference when compared with existing buildings commissioning.

Impacts

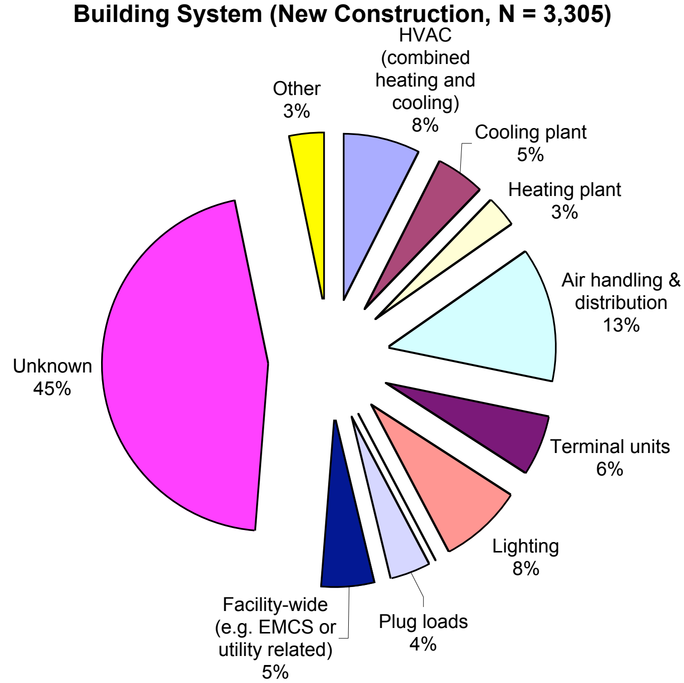
We find that investments in commissioning have yielded positive results, as outlined below.

Deficiencies and measures

Among the 35 new-construction studies reporting, 3305 deficiencies were found in the process of commissioning, with a median value of 28 per building (ranging as high as 705). Deficiencies with air-handling and distribution were the most prevalent, followed by lighting and then HVAC (Figure 31).

The number of corresponding measures was lower, although counting conventions make it difficult to compare the two datasets (Figure 32).[18] The leading measures within the Design, Installation, Retrofit, Replacement category involved installation modifications (143 cases), within Operations and Control involved loop tuning (139 cases), and within Maintenance involved mechanical fixers (174 cases).

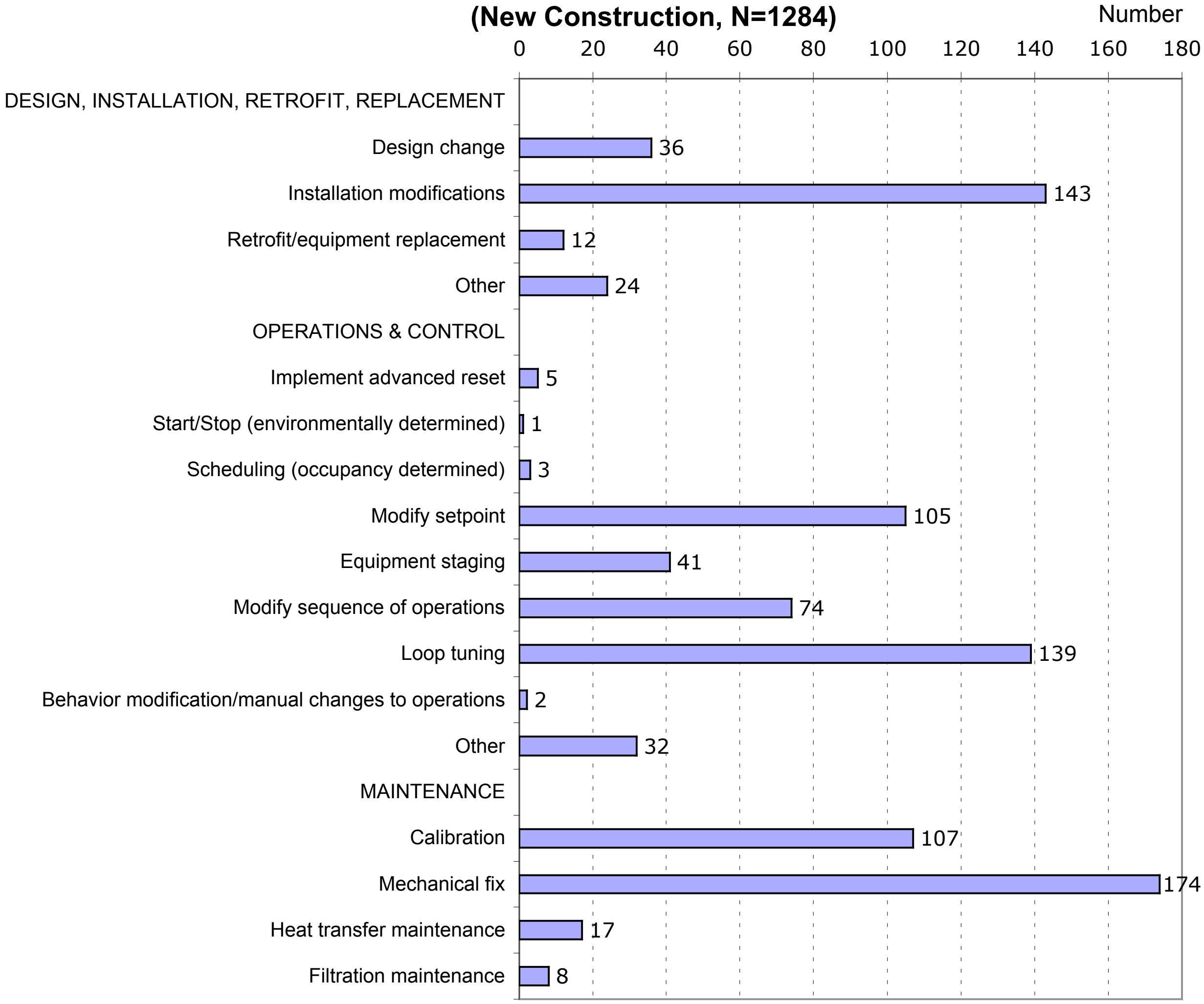
Fig 31. Number of Deficiencies Identified by Building System (New Construction, N = 3,305)



[18] There is not necessarily a one-to-one correspondence between deficiencies and measures.

Within the Operations and Control category, the leading measure was loop tuning (139 cases), and within the Maintenance category, the leading measure was mechanical fixes (174 cases). In our judgment, the virtual absence of measures involving envelopes and plug loads (and perhaps lighting) is probably more reflective of a lack of inspection in these areas than the actual absence of deficiencies. The low level of design changes likely reflects the relatively late stage at which commissioning services are sought.

Fig 32. Frequency of Recommended Measures (New Construction, N=1284)



We compiled Measures Matrices for a subset of new-construction projects analyzed in this study (20 of 69 new-construction commissioning projects). The matrices show the relationship between the building component and system within which a deficiency was found and the type of measure implemented. Among new construction, 157 measures (of a total 1284 tabulated in the study) were mapped in this fashion (Table 10). The table shows the most common combinations of deficiencies and measures. Again, air-handling and distribution ranked as the highest source of deficiencies.

Table 10. Results from Measures Matrices: New construction (20 projects) [yellow highlights indicate most common measures, deficiencies, and combinations]

		Measures																			
		Design, Installation, Retrofit, Replacement				Operations & Control									Maintenance					Deficiency unmatched to specific measure	Total
N (paired) = 157		Design change	Installation modifications	Retrofit/equipment replacement	Other	Implement advanced reset	Start/Stop (environmentally determined)	Scheduling (occupancy determined)	Modify setpoint	Equipment staging	Modify sequence of operations	Loop tuning	Behavior modification/manual changes to operations	Other	Calibration	Mechanical fix	Heat transfer maintenance	Filtration maintenance	Other		
Deficiencies		D1	D2	D3	D4	OC1	OC2	OC3	OC4	OC5	OC6	OC7	OC8	OC9	M1	M2	M3	M4	M5		
HVAC (combined heating and cooling)	**V**	0	8	0	0	2	0	0	3	1	0	1	0	3	6	9	1	2	2	108	146
Cooling plant	**C**	0	3	0	0	0	1	0	1	0	1	1	0	1	1	2	0	0	0	84	95
Heating plant	**H**	1	1	0	0	0	0	0	1	1	1	1	0	1	2	0	0	0	0	49	58
Air handling & distribution	**A**	0	7	2	0	1	0	0	3	0	7	2	0	4	2	14	1	0	3	222	268
Terminal units	**T**	1	5	0	0	0	0	2	5	0	2	1	0	0	3	1	0	1	0	98	119
Lighting	**L**	0	0	0	0	0	0	1	0	0	0	0	0	0	8	1	0	0	0	161	171
Envelope	**E**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plug loads	**P**	0	1	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	81	85
Facility-wide (e.g. EMCS or utility related)	**F**	0	1	0	0	0	0	0	0	1	2	0	0	8	0	3	0	0	0	69	84
Other	**O**	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	108	111
Deficiency unmatched to specific measure		12	82	4	22	0	0	0	90	37	52	133	0	14	78	140	14	3	263		**1137**
Total		14	108	6	22	3	1	3	103	41	66	139	0	31	103	171	16	6	268	**1101**	

Energy savings and cost-effectiveness

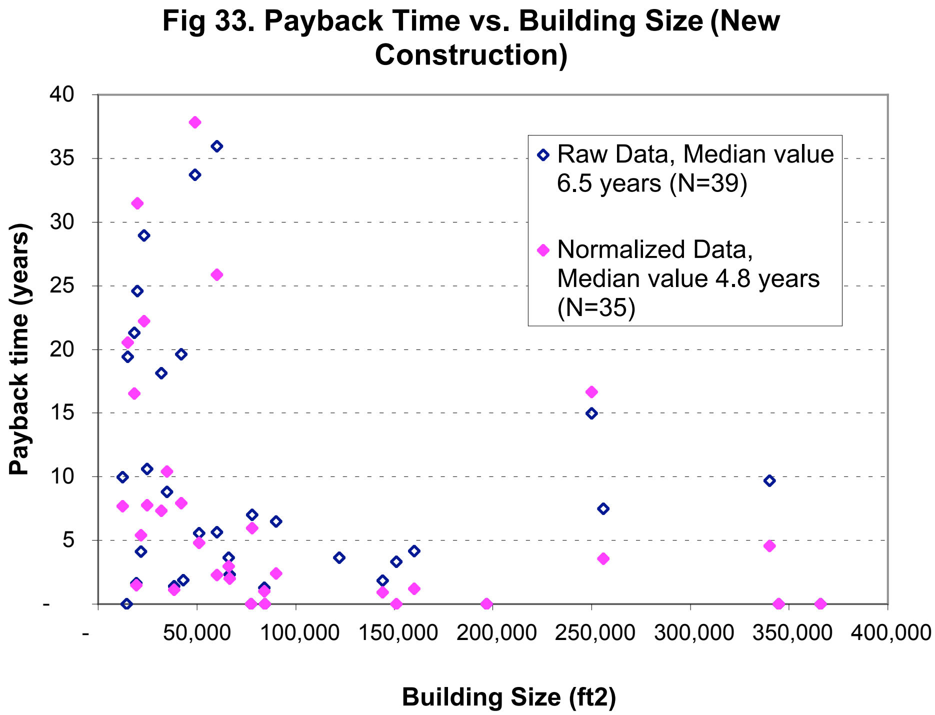
Because of the difficulty in establishing a meaningful simulated baseline, energy savings are rarely estimated for new construction. One study that did so for 16 buildings focused almost exclusively on commissioning the energy-efficiency measures (EEMs) in new construction (Piette *et al.* 1995), finding that commissioning of these measures increased the energy savings by 41 percent (for an average cost "adder" of 8 percent, compared to the direct cost of the energy efficiency measure. Stum *et al.* (1994) observed an average 22-percent increase in EEM savings.

Median estimated total energy savings for our sample was 3.2 kBTU/ft^2-year [0.55 kWh/ft^2-year for electricity, 0.1 W/ft^2-year for peak electrical demand, and 2.2 kBTU/ft^2-year for natural gas]. These include a mix of projects for which commissioning ranged from limited (e.g., to a particular energy efficiency measure) to comprehensive (whole-building).

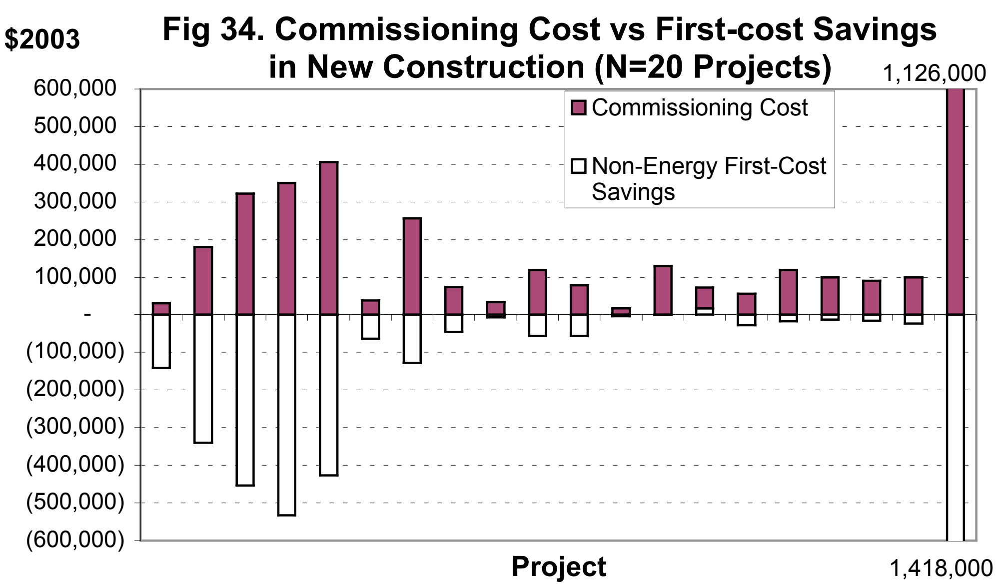
Median energy cost savings were $1,950 per year per building using local un-inflation-corrected costs (N=33), or to $2,500 per year when normalized to national energy prices and $2003 prices (N=27). Savings ranged as high as $306,000 per building per year. Median normalized energy cost savings were $0.05/ft^2-year.

Median payback times of 6.5 years (N=39 projects) were achieved based on the raw data (un-normalized for energy prices or inflation, excluding non-energy impacts), dropping to 4.8 years

(N=35) years for standardized average U.S. energy prices and inflation-corrected commissioning costs (i.e., all costs in $2003). Upper-quartile paybacks were 19.5 and 16.6 years, respectively, while lower-quartile paybacks were 1.9 and 1.2 years, respectively. Normalization for energy prices (including inclusion of non-energy impacts) had a considerable effect on outcomes (Figure 33). Non-energy savings were documented for one-third of the projects, and average payback times for most members of that group were zero (Figure 34). Dorgan *et al.* (2002) assert that, properly done, new-construction commissioning will pay for itself thanks to avoided (non-energy) first costs.



Note: zero values reflect zero net cost (direct commissioning cost minus non-energy savings) Outliers: (69,500; 303), (64,500; 136), (58,000; 77), (29,371; 63)



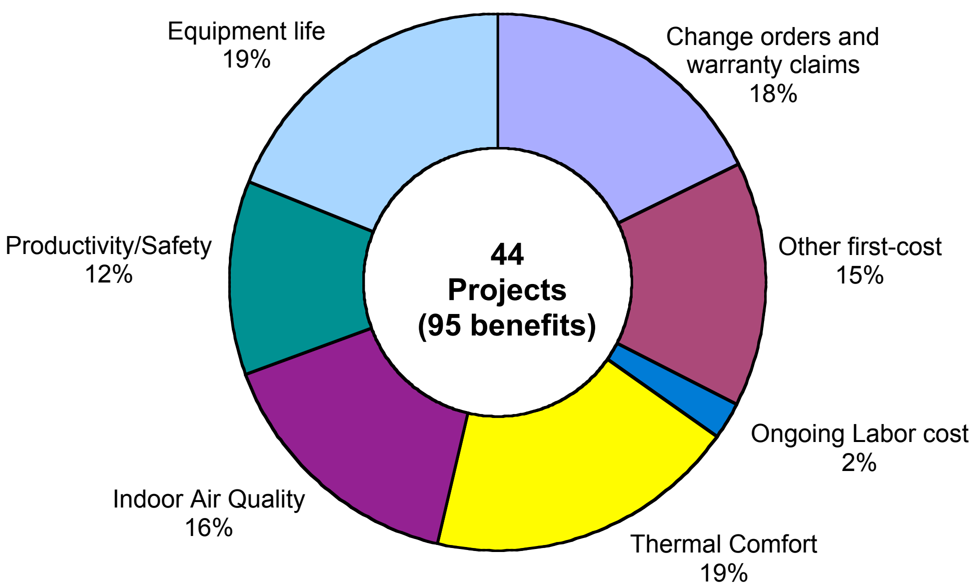
Formation and persistence of savings

Friedman *et al.* (2002 and 2003) present qualitative examples of the persistence of measures fixed during new-construction commissioning. Of 52 items analyzed in ten buildings, 37 were found to persist after several years. The authors note that there is a bias in favor of measures least likely to persist, as they were chosen as the focus of the study. The study suggests that changes in building scheduling and cooling plant control strategies are the most common sources of problems, compounded by limited institutional support of building operators, high operator turnover rates, poor information uptake from the commissioning process itself, and a lack of systems to help operators track energy use and system performance over time (Friedman *et al.* 2002). Only two new-construction projects in our sample provided information on the persistence of savings (and are included in Figure 24).

Non-energy impacts

For 44 new-construction projects in this compilation, information on 95 non-energy benefits were reported by the owner or commissioning provider (Figure 35). Improved equipment lifetime was the most commonly reported: 19 percent of the cases.[19] Other benefits had roughly comparable frequency, including improved indoor air quality, first-cost reductions, labor savings, productivity/safety, and change orders and warranty claims. Ongoing labor-cost impacts are rarely cited. Where the economic value of these impacts (22 cases) was quantified (median value -\$51,000 project – negative value corresponds to savings, positive value to increased cost), we included it in the cost-benefit analysis. The median NEI value was -\$1.24/ft^2 with an inter-quartile range of -\$0.23 to -\$6.95/ft^2.

Fig 35. Reported Non-Energy Impacts (New Construction)



[19] This is often accomplished by reductions in hunting or cycling.

Comparative Assessment of Commissioning in Existing Buildings versus New Construction

The cohort of existing building projects is nearly twenty years older than our new-construction projects (median age of 1978 versus 1996). There are material differences between our results for existing buildings and new construction. This can be seen in the "bottom-line" results per unit floor area—six-fold greater median energy savings and four-fold lower commissioning costs for existing buildings. The combination of higher expenditures and lower floor areas as well as lower energy savings per unit floor area results in lower overall cost-effectiveness for new-construction commissioning than for existing buildings commissioning. Another reason for lower savings is that, for many of the new-construction cases, commissioning targeted only certain components (e.g. energy-efficiency measures), rather than the building as a whole, which skews the results. Due to a small number of high-savings projects, the average savings based on local energy prices are ten-fold greater than median values ($2,500 versus $25,000 per year). Standardizing to national average energy prices reduces the average to approximately $9,200 per year.

It should be noted, in any case, that median payback times (even excluding non-energy benefits) are attractive for existing buildings as well as new construction.

Judging from our sample, building owners appear to exercise different decision rules when determining how much to invest in existing buildings versus new construction commissioning. As seen in Figures 36 and 37, expenditures for new construction commissioning services rise generally along with building size, whereas, with few exceptions, expenditures for existing buildings tend to level out below $50,000. The inference is that in the case of new construction, there is greater willingness to link the level of outlay to the total project cost, whereas larger existing buildings are not usually allocated proportionately more resources for commissioning than are small buildings.

Fig 36. Total Commissioning Cost v Building Size
(excluding non-energy impacts)

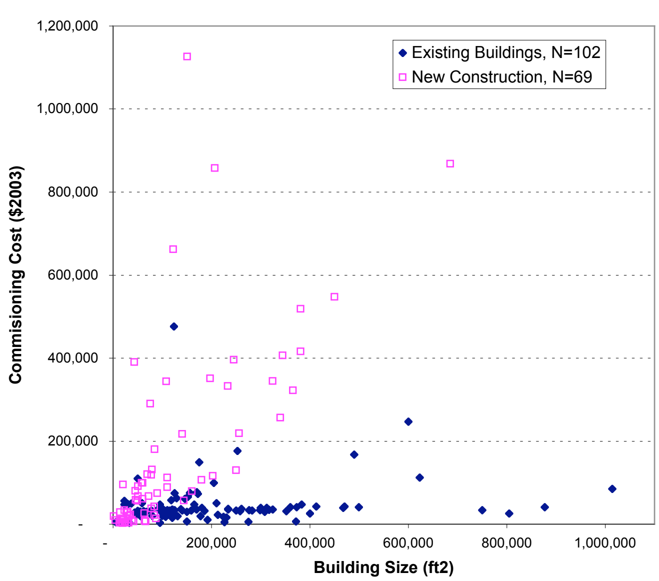
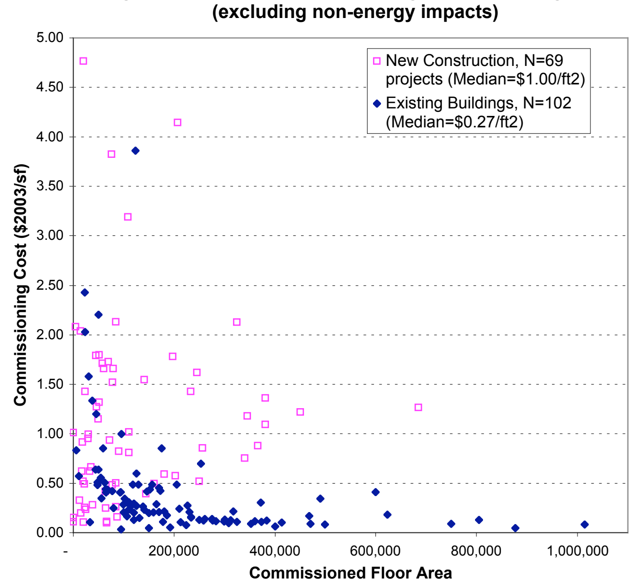


Fig 37. Normalized Commissioning Cost v Building Size
(excluding non-energy impacts)



For projects included in this compilation, the practice of commissioning appears to be more comprehensive for existing buildings than in new construction, as shown previously in Figures 12 and 27. Critical steps are included in only a minority of new-construction projects, a key example of which is design review, which is included in only 20 percent of our sample. Comparably important steps—development of design intent documents and control sequences, reviewing submittals, and construction observation—have similarly low levels of incidence.

As suggested in Figures 11 and 26, new-construction commissioning is more strongly driven by non-energy objectives such as overall building performance, thermal comfort, and indoor air quality whereas existing-building commissioning is more strongly driven by energy savings objectives. This is consistent with our observation that the floor-area-normalized NEIs were seven-fold greater in the case of new construction (Tables 7 and 8).

Reported non-energy benefits are vastly greater for the new-construction cases we compiled than for existing buildings. In fact, in cases where these benefits have been estimated, they often equal or exceed the cost of commissioning (rendering the effective payback time instantaneous). Thus, if fully valued, commissioning of new construction can be equally if not more cost-effective than that for existing buildings.

In both cases, problems with air-distribution systems and correctional measures focusing on operations and control were more pervasive than those with specific pieces of equipment. The need for commissioning in new construction is indicated by our observation that the number of deficiencies identified in new-construction exceed that for existing buildings by a factor of six.

Caveats and Uncertainties

Studies of this nature are always imperfect, as they rely on the availability and quality of primary data source. While on the one hand, our compilation represents a "sample of convenience", it does also represent the majority of published studies, and a significant cross section of unpublished data from commissioning practitioner files. Following are caveats regarding the completeness or uniformity of the data as well as ways in which our results may underestimate true savings. We conclude that, on balance, our results underestimate the true economic benefits.

Potential Sources of Uncertainty or Over-prediction of Savings

- *Non-homogeneity of data.* As this is a meta-analysis, we compiled data originally collected by a variety of individuals, and representing many commissioning providers. As discussed under the Methodology section, above, we standardized and normalized data to the degree possible. To diminish the effect of extreme cases, we emphasize median (as opposed to average) results and provide a quartile analysis to reveal central tendencies.

- *Persistence of energy savings.* We were only able to analyze 20 cases of savings persistence over time. It is important to note that the fast payback times for commissioning measures are most likely significantly shorter than the period of erosion of savings, i.e., commissioning tends to pay for itself even if savings are not permanent. Only two of these studies applied to new construction, and hence more analysis is particularly needed in that arena. To conduct more extensive studies of persistence, a variety of tools are needed, e.g., improved performance monitoring and tracking systems.

- *Inclusion of benefits for measures believed to have been implemented.* Unless all recommendations are implemented "on the spot" by the commissioning provider, time must elapse before it is known which measures were implemented and, thus, what degree of anticipated energy savings captured. In this way, there is a potential that the savings reported were not implemented (58% of the existing-buildings projects partially or fully verified their measures to have been implemented—28% for new construction—others did not report one way or the other), or that savings reported exclude measures that may indeed have ultimately been implemented. Our perspective, however, is that the (sometimes arbitrary) choice by a building owner as to whether or not to implement the commissioning agent's recommendations is not an intrinsic reflection of the commissioning process itself, and, thus, the merits of commissioning should be assessed based on the cost-effectiveness of proposed deficiency resolutions.

Potential Under-estimation of Benefits

- *Inappropriate attribution of costs to the commissioning process.* While commissioning providers identify new-construction deficiencies arising from non-adherence of other parties to the terms of their contracts (e.g., mechanical contractors improperly installing equipment), the costs of correcting them should not be debited to the commissioning process. However, the costs associated with correcting deficiencies identified in existing buildings *are* generally ascribed to the commissioning process. For new and existing buildings alike, major energy-efficiency upgrades that go beyond the correction of a deficiency should be considered "retrofit" costs rather than commissioning costs. These accounting conventions, however, are not always adhered to, resulting in some degree of improper attribution of costs to the commissioning process.

- *Energy savings from all possible measures not captured.* Commissioning is not always applied to the entire building but, rather, may be limited to a given system (e.g., ventilation), given end-use equipment (e.g., to a chiller), or to recently installed energy efficiency measures, especially in new construction. Thus, the average results documented in this report reveal less than the true potential for comprehensive commissioning. Moreover, not all recommended measures are necessarily implemented and those that are implemented are often completed slowly. For example, Piette *et al.* (1995) excluded 92 measures among 16 buildings for which they were unable to estimate energy savings. For seven buildings described by Stum *et al.* (1994) potential energy savings for recommendations not implemented exceeded the savings for those that were implemented. Some sources excluded the prospective energy savings from all un-verified measures.

- *Non-energy impacts are usually not expressed in monetary value.* This can lead to an underestimation of benefits or of costs; the tendency is towards the former. As we saw in Figures (25 and 25), non-energy factors are a big driver for commissioning and are often perceived as part of the benefits. In cases where non-energy-impacts (NEIs) have been estimated, they are significant – often more so than the energy savings. As shown in this study, the payback times were shorter for cases where NEIs were included. In the case of new construction commissioning, we have seen that the value of NEIs can exceed the costs of commissioning, rendering an effectively instantaneous payback time.

- *Underestimation of predicted savings.* In their in-depth study of commissioning in eight buildings (included in our compilation), Bourassa *et al.* (2004) observed that actual savings were, on average 28 percent above predicted levels (based on a one-to-one comparison of implemented measures). Other projects in our compilation exhibited this as well. Thus, measurement of savings seems to be positively associated with greater savings, however the limited available data suggest that more study of this question is required.

- *Financial benefits not fully captured by engineering economics.* Lastly, the most traditional engineering-economics figures of merit (including the simple payback time used in this study) systematically undervalue energy efficiency. This occurs, from the perspective of the building owner, because a building's true market value is a function of net operating income (NOI, gross income minus expenses, which include energy). As NOI rises, so does the building's resale value, and reduced energy costs are one way in which significant increases in NOI can be attained. Excluding this effect tends to "miss" approximately two-thirds of the value created by energy efficiency (Mills 2004).

Conclusions & Recommendations

We have assembled and synthesized the largest sample of real-world data on the energy and non-energy impacts and cost-effectiveness of commercial building commissioning. The following discussion summarizes major findings, implications for energy planning and policy, knowledge gaps and research needs, and some closing thoughts on the way forward.

Major Findings

The performance of today's commercial buildings is compromised by a remarkably diverse array of physical deficiencies, approximately 7,000 examples of which were associated with the buildings included in our compilation. Quality assurance procedures such as those used in building commissioning can, however, address many of these issues, and do so in a cost-effective manner. The solutions resided most frequently in measures involving building controls and operations, as opposed to isolated "hardware" fixes.

Across our sample of 150 existing buildings, we found median whole-building energy savings of 15 percent (average 18 percent) and a corresponding payback time of 0.7 years. Median savings were approximately $45,000 per building ($2003), ranging as high as $1.8 million. For the 74 new-construction cases, we found a median payback time of 4.8 years. Quantifying energy cost savings for new construction is confounded by the lack of baseline data (hypothetical energy use if not commissioned). Addition of non-energy impacts can drastically reduce these payback times, to zero in many cases. We observed cost-effective results across a wide range of building types and sizes, with the most cost-effective results seen among energy-intensive facilities such as hospitals and laboratories. Our results are conservative, insofar the scope of commissioning rarely spans all fuels and building systems in which savings may be found, as not all commissioning recommendations are implemented, and significant first-cost and ongoing non-energy benefits are rarely quantified.

Some see commissioning as a luxury and "added" cost, yet it is only a barometer of the cost of errors promulgated by other parties involved in the design, construction, or operation of buildings. Commissioning agents are just the "messengers"; they are only revealing and identifying the means to address pre-existing problems.

While not a panacea, we find that building commissioning is one of the most cost-effective and far-reaching means of improving the energy efficiency of buildings, with applications across a large segment of the U.S. building stock. For example, the "Five-Lab Study" (Interlaboratory Working Group 1997) provided a major assessment of U.S. buildings energy savings potential, and found an electricity savings potential of approximately 180 billion kilowatt-hours per year in the commercial sector by the year 2010 at a levelized cost of conserved energy (CCE) of approximately $0.01/kWh. Assuming a conservative five-year measure life, the median CCE of our existing building sample is one-tenth of that for the aforementioned "hardware" measures, i.e., $0.001/kWh.

Implications for Energy Planning & Policy

While the potential is enormous, a vanishingly small fraction of the U.S. commercial buildings stock has as yet been commissioned.[20] If the results observed across our sample are representative of the practice and potential of commissioning, significant energy savings could be achieved nationally. Specifically, if our average project performance were to be achieved over the entire building stock (essentially an economic-potential, not adjusted for partial penetration rates) the full cost-effective potential would amount to 15-percent savings of the $120-billion annual energy bill for the sector (as of 2002, see USDOE 2004). This translates into savings of $18 billion annually among existing commercial buildings – and significantly more if best practices (i.e., the upper-tier of savings seen among sample) became the standard. In practice, an unknown fraction of the full stock could be reached.

Coupled with design intent documentation, commissioning provides a way to define measurable performance targets and evaluate as-built and as-operated system conditions (Mills *et al.* 2002). It is, however, important not to view commissioning in isolation, but rather as part of an integrated strategy for improving building energy performance. For example, commissioning interoperates with diagnostics, end-use monitoring, and the implementation of the entire spectrum of energy-efficiency measures.

Commissioning is perhaps best understood as a form of risk management. At the individual facility level, it helps ensure that funds are spent wisely and that the intended energy savings targets are achieved in practice. At the regional or national level, commissioning essentially safeguards macro-level goals for energy savings and other benefits such as the reduction of greenhouse-gas emissions. The ultimate efficacy of energy efficiency research and development portfolios, as well as deployment programs, lies in no small part in the extent to which they are coupled with quality assurance in design and delivery. As we saw earlier in the case of US Department of Energy "high-performance building" demonstrations, it can be difficult to attain projected savings in practice (Torcellini *et al.* 2004).

Knowledge Gaps and Research Needs

Although this is the most comprehensive study to date, there remains value in compiling more case studies in a manner consistent with the methodology developed here. This would fortify the existing compilation, allowing more detailed analyses (e.g., outcomes by type of building) and more definitively determine actual costs in practice. This would naturally be complemented with activities to determine best practices in terms of minimizing costs and maximizing energy savings, cost-effectiveness, and market uptake of commissioning practice. It is also important to internationalize the data collection effort.

The current sample has a high proportion of public buildings (schools, hospitals, public order and safety, etc), and should be expanded to include more privately owned and operated facilities. Additional building types, e.g., cleanrooms, data centers, and industrial facilities should also be

[20] Nearly 100 percent of the U.S. commercial building stock is eligible for commissioning, according to the NSF/IUCRC Center for Building performance and Diagnostics at Carnegie Mellon University, Advanced Building Systems Integration Consortium, Guidelines for High Performance Buildings. This group estimates the savings potential at between 2 percent and 27 percent, based on a sample of eleven projects.

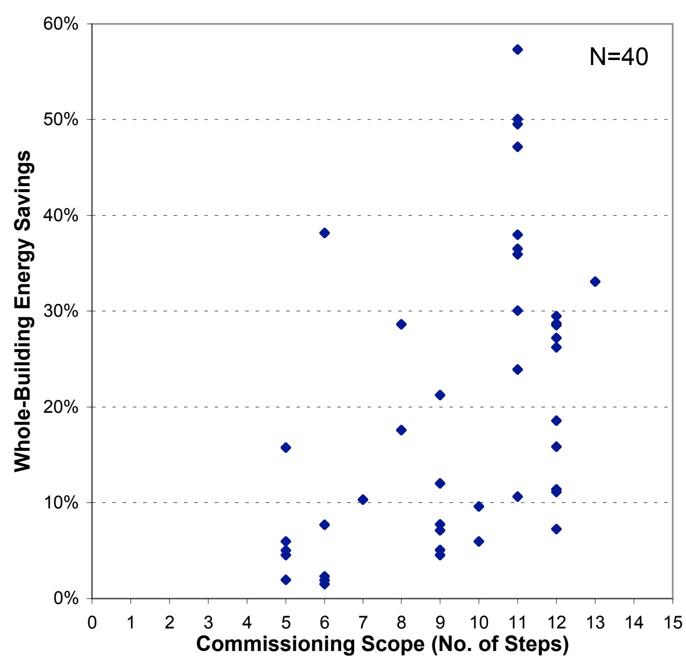
explored–and are today remarkably absent from the commissioning literature. Similarly, particular cohorts (e.g., LEED buildings and building-integrated renewable energy systems) should be analyzed. Analyzing the types and number of problems with high-performance buildings as well as their energy use compared to a modeled goal will make the effectiveness of advanced energy savings technologies clearer and enhance understanding of the importance of commissioning these facilities.

Other subsets of the data should be analyzed, e.g., grouping the projects by level and type of commissioning effort. Using data like those collected here, models could be developed to predict commissioning costs and savings as a function of building location, characteristics, fuel choices, etc. Our existing database would also support analysis of the cost-effectiveness of specific commissioning measures in specific building systems.

Few if any commissioning efforts today focus on peak electrical demand, and none in our compilation focused on a new generation of "demand-responsiveness" technologies and strategies, which, due to their complexity and novelty, will no doubt present even a greater need for commissioning than conventional systems.

Commissioning takes many forms, both in the breadth and depth with which it is applied to a given project. A key outstanding question is the appropriate level of effort, and the relative benefits of in-depth versus superficial commissioning efforts. Figure 38 presents whole-building energy savings versus the number of steps (from Figure 12) involved in the existing-building commissioning projects in our database. The relationship suggests that savings rise with increasingly comprehensive commissioning, but the question deserves more investigation. Payback times do not correlate with depth of commissioning. (Insufficient data were available to do the analysis for new-construction commissioning.)

Fig 38. Savings vs. Depth of Commissioning (Existing Buildings)



As a part of this ongoing cost-benefit research, the persistence of benefits should also continue to be analyzed, both from the bottom-up (do individual measures persist?) and top-down (how does energy use change over time?).

Energy-efficiency R&D portfolios—be they in the public or private sector—routinely focus on specific technologies or physical systems. Less well attended to are process-oriented strategies such as commissioning. It is clear from our analysis that commissioning cannot only generate energy savings in its own right (e.g., by starting with "ordinary" buildings that are not particularly energy-efficient), but can also ensure the performance of energy-efficiency technologies. The latter is especially important for "emerging" technologies that tend to be more complex and less well-understood than status-quo technologies.

While providing many answers to long-standing questions about the cost-effectiveness of commissioning, this study has also identified a number of appropriate research and analytical opportunities, including:

- Create and improved and expanded set of performance metrics to use in evaluating commissioning experience.

- Improve the capture of deficiency data. We noted that there was a significant proportion of deficiencies categorized as "other" or "unknown", roughly one-half the total logged.

- Develop methods for identifying and accounting for instances in which on-site personnel would have identified and corrected deficiencies without the contribution of commissioning providers.

- Reconcile the durability or persistence of commissioning measures—essentially "measure life"—and the optimal frequency with which to commission. Only eighteen examples exist for existing buildings and only two for new construction.

- Study "outlier" data-points to enhance understanding of both best and worst practices.

- Improve methods for identifying and quantifying non-energy impacts.

- Validate or refute the observed correlation of measurement of commissioning savings with deeper savings. Correlation may not equate to causation in this case.

- Develop better and more disaggregated estimates of the national savings potential, including a breakdown by building type and new versus existing.

A final important area of research is performance monitoring and diagnostics. One reason commissioning issues occur is that building operators are unaware that problems exist. An economizer damper may be stuck, or a variable-frequency drive control may be disabled limiting efficient operations and causing energy waste. New emerging technologies and ongoing research to develop performance monitoring and diagnostics tools offer the capability to detect and diagnose the root cause of such problems. Improved performance monitoring systems are needed to ensure critical measurements are available to detect problems. Numerous techniques for fault detection and diagnosis have been explored, including neural nets, physical dynamic models, and simple engineering rules. Research by Friedman and Piette (2001) examined a variety of tools currently in use. Further research is underway to develop performance monitoring specifications and robust diagnostic systems. New information technology and web-based energy information systems offer improved performance monitoring capabilities and platforms to host diagnostic tools (2003).

The Way Forward

The fledgling field of commercial buildings commissioning has many innovative pioneers and, judging from the results of this study, their efforts have been effective. However, energy-oriented commissioning has attained a vanishingly small penetration rate. Future case-study research should be informed by market research designed to better understand what information decision-makers require, and how to best present it. Data-collection efforts should be focused on filling those information gaps, and better understanding the processes and reasons by which commissioning recommendations are accepted or rejected in practice.

As buildings and the technologies within them become more complex and interconnected, the need for commissioning will increase. Education remains an important strategy for building the capacity for commissioning services in the marketplace and awareness among building owners and operators. For example, our samples of new and existing buildings alike showed that reduced equipment breakdown was the largest perceived non-energy benefit cited after commissioning was completed, yet it was never cited as a reason for originally embarking on the commissioning process.

Cost-benefit analyses such as those presented here will help program decision-makers weigh the cost-effectiveness of commissioning in their planning decisions, while enabling building owners to be more confident in undertaking the commissioning process. We invite others to contribute new case-study data to this compilation. [21]

[21] Practitioners are invited to send data for inclusion in the database presented in this report. Information can be entered into the spreadsheet available at http://eetd.lbl.gov/emills/PUBS/Cx-Costs-Benefits.html and addressed to emills@lbl.gov. The aforementioned California Commissioning Collaborative database (Friedman *et al.* 2004) is also accepting contributions or more in-depth case studies.

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APPENDICES

Appendix A. Data Instrument

Data Collection Instrument for LBNLCommissioning Cost-Benefits Analysis			
Version: November 15, 2004	Units	Notes	EXAMPLE
PROJECT DESCRIPTION			
Name of person completing this entry	text		John Doe
Case Identifier	PECI-#, TAMU-#, LBNL-#, etc.	For internal tracking	Project 1-Rx
Commissioning provider			Commissioners Inc (Seattle, WA)
Existing building (RCx); New construction (Cx)	Cx; RCx	new	RCx
Was the building previously commissioned?	Y; N	existing	N
Commissioning project leader's level of experience	number of projects previously completed (number only; no text)	Applies to project leader, not firm. Do not include general "energy efficiency experience"; R/Cx only	75
Building name and street address (if PUBLIC INFORMATION)	text	Data will be included in final report	Courthouse
Building name and street address (if CONFIDENTIAL)	text	Data will be kept confidential, I.e. not included in final report	
Location - City	text		Boise
Location - State	Postal Abbreviation		ID
Building Ownership	Public; Private		Public
Level of (retro)commissioning	Comprehensive, Specific Systems	E.g. if only the energy-efficiency measures were commissioned, answer would be "SE"	C
Number of buildings	Number	When unknown, enter "1"	1
Year construction completed	Year (NNNN)	Use four-digit format	1977
Total building construction cost (if new building) [$]	$	If not known, est $200/sf	
Year commissioning project completed	NNNN	Use four-digit format	2003
Year that (retro)commissioning costs reported below were incurred [NNNN]	NNNN	If multi-year project, list mid-point	2002
Floor Area:			
Entire building	square feet		23,210
Floor area served by commissioned systems	square feet		23,210
Net or Gross; Parking areas	N(p); G(p)	Include "(p)" in code if data include parking/garage spaces. Preferably, exclude parking areas.	N
Is the facility part of a campus with central heating and/or cooling?	Y; N		N
Building type(s)			Public Assembly
Education			
K-12	"	"	
Higher education	"	"	
Food Sales	"	"	
Food Service	"	"	
Health Care			
Inpatient	"	"	
Outpatient	"	"	
Laboratory	"	"	
Lodging	"	"	
Mercantile			
Retail	"	"	
Service	"	"	
Office	"	"	
Public Assembly	"	"	23,210
Public Order and Safety	"	"	
Religious Worship	"	"	
Service	"	"	
Warehouse and Storage	"	"	
Other	"	"	
Vacant	"	"	

REASONS FOR (RETRO)COMMISSIONING	Place an "x" by the appropriate answer(s)	Put an "x" in this row if ANY value is checked in the column	x
Ensure system performance (energy and non-energy-related systems)	"		
Obtain energy savings	"		x
Ensure or improve thermal comfort	"		x
Extended equipment life			x
Train and increase awareness of building operators	"		
Smoother process and turnover (new construction)	"		
Increase occupant productivity	"		
Ensure adequate indoor air quality	"		x
Comply with LEED or other sustainability rating system	"		
Reduce liability	"		
Qualify for rebate, financing, or other services	"		
Research/demonstration/pilot	"		x
Participation in utility program	"		
Other	free text	Add brief description	
DEFICIENCIES & STRATEGIES	"Count" should agree with that in the "Measures" worksheet for the items that apply.	If information is available, complete separate "Measures" worksheet first. Definitions available on "Measures" Tab.	
"Measures Tab" completed?			Y
Number of Problems Identified, by Component:			
HVAC (combined heating and cooling)	"	"	4
Cooling plant	"	"	1
Heating plant	"	"	2
Air handling & distribution	"	"	3
Terminal units	"	"	2
Lighting	"	"	2
Envelope	"	"	0
Plug loads	"	"	0
Facility-wide (e.g. EMCS or utility related)	"	"	2
Unknown			
Other	"	"	0
Number of Measures Recommended To Resolve Problems:		Includes accepted as well as rejected measures.	
DESIGN, INSTALLATION, RETROFIT, REPLACEMENT			
Design change	"	"	0
Installation modifications	"	"	0
Retrofit/equipment replacement	"	"	2
Other	"	"	5
OPERATIONS & CONTROL			
Implement advanced reset	"	"	0
Start/Stop (environmentally determined)	"	"	0
Scheduling (occupancy determined)	"	"	1
Modify setpoint	"	"	0
Equipment staging	"	"	1
Modify sequence of operations	"	"	1
Loop tuning	"	"	0
Behavior modification/manual changes to operations	"	"	2
Other	"	"	0
MAINTENANCE			
Calibration	"	"	0
Mechanical fix	"	"	3
Heat transfer maintenance	"	"	1
Filtration maintenance	"	"	0
Other	"	"	0
UNKNOWN			
Diagnostics and Automation Techniques	Text	List tools/methods used, e.g. WBD, ACRX, PacRat, Enforma	
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Subsequent cost and savings data entered should exclude that for recommended measures known to have been rejected.	Yes-all

(RETRO)COMMISSIONING COST DATA		Give costs in year of original data; do not correct for inflation	
Total commissioning cost [nominal $]	$ (in currency of year reported above as year commissioning was completed)	Should include study costs. Should not include TAB.	45,351
Of which, Cx Agent Fee [$]			27,500
What % of total is represented by non-energy-related measures (e.g. security system cx), if cost and/or savings data are included below?	%		10%
Cost Paid By:			x
Building owner	% (enter as decimal value)	Enter "0" if not applicable	50%
Utility (e.g. as rebate)	% (enter as decimal value)	Enter "0" if not applicable	100%
Other (e.g. research grant)	% (enter as decimal value)	Enter "0" if not applicable	
Cost Breakdown, by Phase:			
New Construction (Cx)			
Design Review	% of total cost		
Construction Observation	% of total cost		
Acceptance Testing	% of total cost		
Warranty	% of total cost		
Existing Buildings (RCx)			100%
Investigation and Planning	% of total cost		15%
Implementation	% of total cost		63%
Verification & Persistance Tracking	% of total cost		12%
Reporting	% of total cost		10%
Labor	$		19,126
Unpaid/unbilled labor	hours		
Supplies and equipment costs	$		40
Utility rebate	nominal$		20,076
Travel	$		910
Scope of (Retro)commissioning: Items Included in Reported Costs			
Commissioning (new buildings)			
Stage Commissioning Begun (new construction only)	**D**esign, **C**onstruction, **A**cceptance, **S**tartup	Enter: "D", "C", "A", or "S"	
Cx Provider development of design intent documents	Y; N (do not leave blank unless unknown)	Complete only if new building	
Write Cx Specifications	"	Complete only if new building	
Develop Cx Plan	"	Complete only if new building	
Design Review (indicate # of review cycles)	"	Complete only if new building	
Develop Sequences of operation (if not well-developed by mech or controls contractor)	"	Complete only if new building	
Review submittals	"	Complete only if new building	
Construction observation	"	Complete only if new building	
Verification checks/prefunctional testing	"	Complete only if new building	
Functional testing	"	Complete only if new building	
Cx Provider significantly involved in issue resolution	"	Complete only if new building	
Oversee training	"	Complete only if new building	
Review O&M Manuals	"	Complete only if new building	
Develop systems manual/recommissioning manual	"	Complete only if new building	
Perform trend analysis	"	Complete only if new building	
Evaluate energy cost savings	"	Complete only if new building	
Final Cx Report	"	Complete only if new building	

Retro-commissioning (existing buildings)		Enter "x" if yes	x
Document design intent or update current documentation	Y; N (do not leave blank unless unknown)	Complete only if existing building	Y
Develop RCx Plan	"	Complete only if existing building	Y
Perform utility bill analysis, benchmarking	"	Complete only if existing building	Y
Perform trend analysis	"	Complete only if existing building	Y
Building modeling	"	Complete only if existing building	Y
Document master list of findings	"	Complete only if existing building	Y
Estimate energy cost savings for findings	"	Complete only if existing building	Y
Present a findings and recommendations report	"	Complete only if existing building	Y
Update system documentation (control sequences)	"	Complete only if existing building	N
Implement O&M improvements	"	Complete only if existing building	Y
Implement capital improvements	"	Complete only if existing building	Y
Monitor fixes	"	Complete only if existing building	Y
Measure energy savings	"	Complete only if existing building	N
Develop systems manual/recommissioning manual	"	Complete only if existing building	N
Final RCx Report	"	Complete only if existing building	Y
BASELINE ENERGY USE AND SAVINGS			
End uses included in following data [Whole Building, or finite set of end uses based on "Components" defined above]	WB or C	Do not include savings estimates for measures known not to have been implemented	WB
Are data weather-normalized?	Y;N		Y
If yes, using what method?	name method		Degree-day normalization
Year of Energy Cost Data	Year (NNNN)	If possible, do not use first post-commissioning year's data (savings often manifest slowly). Use year-2 or -3.	2001
Total Electricity usage:			
Before commissioning	kWh/year		482,000
After commissioning (or as-commissioned, if new building)	kWh/year		327,808
Savings	kWh/year		154,192
Total Electric Peak Demand			
Before commissioning	peak kW		
After commissioning (or as-commissioned, if new building)	peak kW		
Savings	peak kW		
Total Fuel usage:		"	
Before commissioning	Millon BTU/year		1,204
After commissioning (or as-commissioned, if new building)	Million BTU/year		890
Savings	Million BTU/year		314
Thermal (Total chilled water, hot water, and steam)		Enter information here ONLY if it is not available separately for HW, CW, and Steam (in which case, add separately in the following three sub-sections)	
Before commissioning	Million BTU/year		
After commissioning (or as-commissioned, if new building)	Million BTU/year		
Savings	MMBTU/year		
Total Hot water			
Before commissioning	Million BTU/year		
After commissioning (or as-commissioned, if new building)	Million BTU/year		
Savings	MMBTU/year		
Total Steam			
Before commissioning	Million BTU/year		
After commissioning (or as-commissioned, if new building)	Million BTU/year		
Savings	MMBTU/year		
Total Chilled water			
Before commissioning	Million BTU/year		
After commissioning (or as-commissioned, if new building)	Million BTU/year		
Savings	MMBTU/year		

Total energy cost (electric, peak, fuel):	$/year		
Before commissioning	$/year	No inflation correction	32,524
After commissioning (or as-commissioned, if new building)	$/year	No inflation correction	22,670
Nominal Savings (current year prices, no inflation-correction)	$/year-project	No inflation correction	9,854
Energy prices associated with cost estimates		Use values corresponding to cost data provided above	
electricity	$/kWh		0.048
peak electricity demand	$/kW-Month		
fuel	$/million BTU		7.80
purchased thermal energy (hot/cold water and/or steam)	$/million BTU		
Hot water			
chilled water			
steam			
Energy Savings Determination [select answers that correspond to the energy data given in prior rows]	A; B; C; D; or E	If multiple methods are used, choose ONE of the following to reflect the most prevalent form of determination.	D
Engineering Estimates/Simulations (no measurements) = "E"	Y;N		N
Measured Savings - IPMVP Option A. Partially measured retrofit isolation	Y;N	IPMVP Category: See "M&V Options Tab for definitions"	N
Measured Savings - IPMVP Option B. Retrofit isolation	Y;N	IPMVP Category: See "M&V Options Tab for definitions"	N
Measured Savings - IPMVP Option C. Whole facility	Y;N	IPMVP Category: See "M&V Options Tab for definitions"	N
Measured Savings - IPMVP Option D. Calibrated simulation	Y;N	IPMVP Category: See "M&V Options Tab for definitions"	Y
Do the preceeding savings data reflect all commissioning activities described and costed above?	Y;N		Y
If "no", list % increase in reported savings anticipated (for measures known to be slated for implementation)	%	will be used to modify raw savings data (if applicable)	
Persistence of Energy Savings (existing buildings) or Performance (new construction)	Persistence of Energy Savings or Performance (fraction of energy consumed relative to base year; normalized to floor area,) [electric; fuel]	If available, also provide notation on the persistence of individual measures, via the column provided in the "Measures" tab.	
Year 0 (pre-commissioning)	ratio (Electricity; Fuel; CHW; HW; Steam)	1.00; 1.00; 1.00; 1.00; 1.00	1.00; 1.00
Year 1	ratio (Electricity; Fuel)	ratios	0.68; 0.74
Year 2	ratio (Electricity; Fuel)	ratios	0.72; 0.76
Year 3	ratio (Electricity; Fuel)	ratios	0.65; 0.70
Year 4	ratio (Electricity; Fuel)	ratios	0.60; 0.69
Year 5	ratio (Electricity; Fuel)	ratios	
Year 6	ratio (Electricity; Fuel)	ratios	
If one or more periods include changes in occupancy, schedules, equipment, energy prices, or occupied floor area, are these adjusted for in the preceding estimates?	Y/N		

NON-ENERGY IMPACTS			
First-Cost Savings			x
Change orders and warranty claims	$	Show reductions as a negative value; increases as a positive value	
Other first-cost	$	"	
Ongoing (recurring) Cost Savings			
Ongoing Labor cost	O&M; C, P, D, CO; IR, O	Reduction/increase (O&M, Complaints, Productivity, Downtime, Information Requests, Other):	
Labor	person-hours/year	Show reductions as a negative value; increases as a positive value	
Cost	$/year	"	1,200
Other			
Thermal Comfort	Y;N	"	Y
	$/year	"	
Indoor Air Quality	Y;N	"	Y
	$/year	"	
Productivity/Safety	Y;N	"	Y
	$/year	"	
Tenant retention; turnover	Y;N	"	N
	$/year	"	
Liability	Y;N	"	N
	$/year	"	
Equipment life	Y;N	"	Y
	$/year	"	200
Other (or combination of above)	Y;N	"	
	$/year	"	
OTHER			
Data Source(s)	text	Use, abbreviated citation here (e.g. "Claridge et al. 1999") and report full bibliographic info on the "Data Sources" Tab next to the row representing this project.	Smith, J. 2002. "Commissioning of the City Hall". Technical report 12345
Comments (summarize concisely here; attach Tabs if desired)	text		

Appendix B. Analytic Assumptions

1. New Building Construction Cost 150 $2003/ft2 Used to estimate construction cost where only floor area is available

2. Standardized energy price assumptions (commercial customers, $2003)

Electricity	0.0786	$/kWh
Gas	8.04	$/million BTU
Hot/Chilled water; Steam	9.00	$/million BTU
Peak electrical demand	10.00	$/kW-month

Source for gas and electric: DOE/EIA http://www.eia.doe.gov/emeu/states/_states.html; and Monthly Energy Review

Estimating range of prices for delivered hot water, chilled water, or steam: Examples using preceding energy feedstock prices

Hot Water (gas fuel)		
	85%	generation efficiency
	95%	distribution efficiency
	9.95	$/MMBTU
Chilled Water (gas-absorption cycle - electricity)		
	80%	production efficiency
	1.00	COP -- Range: about 0.7 for single effect; 1.1 for double effect (most common)
	95%	distribution efficiency
	10.57	$/MMBTU
Steam: (steam boiler - natural gas)		
	80%	generator efficiency
	90%	distribution efficiency
	11.16%	$/MMBTU
Cogeneration as source (natural gas fuelstock)		
	0.3	input to electricity
	0.67	.67 avail waste heat (so, 2/3 of fuel price allocated to heat production, balance to power)
	80%	heat recovered
	90%	distribution efficiency
	7.48	$/MBTU

3. Decision Rules re: building or commissioning project ventages

Lacking other data, building age set to 1 year prior to date of publication of new-construction commissioning source documents

Lacking year of energy data, we set it to the date of completion of commissioning project

4. Deflators

Year	Energy prices [a]	Cx Labor prices [b]	Construction costs [c]
1970			0.21
1971			0.24
1972			0.26
1973			0.28
1974			0.30
1975			0.33
1976			0.36
1977			0.38
1978			0.41
1979			0.45
1980	0.50		0.48
1981	0.55		0.53
1982	0.59		0.57
1983	0.61		0.61
1984	0.63	*2.07*	0.62
1985	0.65	2.01	0.63
1986	0.67	1.94	0.64
1987	0.69	1.88	0.66
1988	0.71	1.82	0.68
1989	0.74	1.74	0.69
1990	0.77	1.66	0.71
1991	0.79	1.61	0.72
1992	0.81	1.57	0.74
1993	0.83	1.52	0.78
1994	0.85	1.47	0.81
1995	0.87	1.40	0.82
1996	0.88	1.36	0.84
1997	0.90	1.30	0.87
1998	0.91	1.24	0.88
1999	0.93	1.19	0.91
2000	0.95	1.13	0.93
2001	0.97	1.07	0.95
2002	0.98	1.04	0.98
2003	1.00	1.00	1.00

[a] EIA, Annual Energy Review 2002, Oct. 2003, Appendix D, p. 353. (from BTS Core data book)
[b] Construction Labor: http://www.bea.doc.gov/bea/dn1.htm
[c] McGraw Hill - Engineering News Record, Construction Cost Index
http://enr.construction.com/features/conEco/costIndexes/constIndexHist.asp

Appendix C. Measure Definitions

Design, Installation, Retrofit, Replacement	Code
Design, Installation, Retrofit, Replacement Design problems found and corrected during design review of a new building (Cx), a design problem physically corrected or circumvented (during Cx or RCx). [Problems with the design of control sequences are accounted for under "Control".]	**D1**
Installation modifications To address improper installation of equipment, sensors, distribution systems, etc.	**D2**
Retrofit/equipment replacement RCx strategies to improve the performance of a system, as distinct from a change in design [treated above].	**D3**
Other Other design, installation, retrofit, or replacement measures.	**D4**
Operations & Control	
Implement advanced reset Recommended modifications to reset schedules of HVAC processes. E.g., Supply Air Temperature reset based on Outside Air Temperature.	**OC1**
Start/Stop (environmentally determined) Recommendations that affect environmentally determined equipment control settings (e.g., chiller or boiler lockouts that based on out side air dry bulb temperature or seasonally determined equipment operation).	**OC2**
Scheduling (occupancy determined) Recommendations affecting the control of equipment availability as a function of building occupancy (e.g. lighting sweeps; temperature setbacks; morning warm-up).	**OC3**
Modify setpoint Recommendations that modify the setpoint of a control loop. E.g., Supply air temperature setpoint, thermostat setpoint, or static pressure setpoint.	**OC4**
Equipment staging Recommendations that affect control settings for the availability or staging of duplicate equipment, e.g., Chiller staging and loading sequence or lead-and-lag pumping sequences.	**OC5**
Modify sequence of operations Recommendations that propose changes significant enough to be considered a major modification to the building's existing sequence of operations.	**OC6**
Loop tuning Modify control loop parameters to improve control (reduce cycling, hunting, oscillations).	**OC7**
Behavior modification/manual changes to operations Recommendations that seek to modify the behavior of the building staff or occupants or instruct building staff or occupants on the proper use of equipment (e.g. turning off lights upon leaving a room, correctly manipulating the system in response to complaint calls).	**OC8**
Other Other operations & control measures.	**OC9**
Maintenance	
Calibration Recommendations that address calibration problems with equipment or systems.	**M1**
Mechanical fix Replacing belts, broken linkages, motor maintenance, etc.	**M2**
Heat transfer maintenance Coil cleaning, cooling tower water treatment, correcting refrigerant charge	**M3**
Filtration maintenance Changing filters, modifying filter racks, changing filter type, etc.	**M4**
Other Other maintenance measures.	**M5**

Appendix D. Performance Measurement & Verification Definitions

(Source: IPMVP 2001)

Table 1: Overview of M&V Options

M&V Option	How Savings Are Calculated	Typical Applications
A. Partially Measured Retrofit Isolation Savings are determined by partial field measurement of the energy use of the system(s) to which an ECM was applied, separate from the energy use of the rest of the facility. Measurements may be either short-term or continuous. Partial measurement means that some but not all parameter(s) may be stipulated, if the total impact of possible stipulation error(s) is not significant to the resultant savings. Careful review of ECM design and installation will ensure that stipulated values fairly represent the probable actual value. Stipulations should be shown in the M&V Plan along with analysis of the significance of the error they may introduce.	Engineering calculations using short term or continuous post-retrofit measurements and stipulations.	Lighting retrofit where power draw is measured periodically. Operating hours of the lights are assumed to be one half hour per day longer than store open hours.
B. Retrofit Isolation Savings are determined by field measurement of the energy use of the systems to which the ECM was applied, separate from the energy use of the rest of the facility. Short-term or continuous measurements are taken throughout the post-retrofit period.	Engineering calculations using short term or continuous measurements	Application of controls to vary the load on a constant speed pump using a variable speed drive. Electricity use is measured by a kWh meter installed on the electrical supply to the pump motor. In the baseyear this meter is in place for a week to verify constant loading. The meter is in place throughout the post-retrofit period to track variations in energy use.
C. Whole Facility Savings are determined by measuring energy use at the whole facility level. Short-term or continuous measurements are taken throughout the post-retrofit period.	Analysis of whole facility utility meter or sub-meter data using techniques from simple comparison to regression analysis.	Multifaceted energy management program affecting many systems in a building. Energy use is measured by the gas and electric utility meters for a twelve month baseyear period and throughout the post-retrofit period.
D. Calibrated Simulation Savings are determined through simulation of the energy use of components or the whole facility. Simulation routines must be demonstrated to adequately model actual energy performance measured in the facility. This option usually requires considerable skill in calibrated simulation.	Energy use simulation, calibrated with hourly or monthly utility billing data and/or end-use metering.	Multifaceted energy management program affecting many systems in a building but where no baseyear data are available. Post-retrofit period energy use is measured by the gas and electric utility meters. Baseyear energy use is determined by simulation using a model calibrated by the post-retrofit period utility data.

E . Estimated. Based on engineering calculations, only

Table 1:Overview of New Construction M&V Options

M&V Option	How Baseline is Determined	Typical Applications
A. Partially Measured Retrofit Isolation Savings are determined by partial measurement of the energy use of the system(s) to which an ECM was applied, separate from the energy use of the rest of the facility. Some parameters are stipulated rather than measured.	Projected baseline energy use is determined by calculating the hypothetical energy performance of the baseline system under post-construction operating conditions.	Lighting system where power draw is periodically measured on site. Operating hours are stipulated.
B. Retrofit Isolation Savings are determined by full measurement of the energy use and operating parameters of the system(s) to which an ECM was applied, separate from the rest of the facility.	Projected baseline energy use is determined by calculating the hypothetical energy performance of the baseline system under measured post-construction operating conditions.	Variable speed control of a fan motor. Electricity needed by the motor is measured on a continuous basis throughout the M&V period.
C. Whole Facility Savings are determined at the whole-building level by measuring energy use at main meters or with aggregated sub-meters.	Projected baseline energy use determined by measuring the whole-building energy use of similar buildings without the ECMs.	New buildings with energy-efficient features are added to a commercial park consisting of buildings of similar type and occupancy.
D. Calibrated Simulation Savings are determined at the whole-building or system level by measuring energy use at main meters or sub-meters, or using whole-building simulation calibrated to measured energy use data.	Projected baseline energy use is determined by energy simulation of the Baseline under the operating conditions of the M&V period.	Savings determination for the purposes of a new building Performance Contract, with the local energy code defining the baseline.

E . **Estimated.** Based on engineering calculations, only

Source: http://www.ipmvp.org

APPENDIX E. Catalog of Projects (summary)

ID	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider		TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)
Building name and location		Zachry; Texas A&M University	Materials Research Institute (MRI)	Biology	Capitol Building	S.F. Austin Building & CP	John H. Reagan Building	Insurance Building	Archives Building	Starr Building	Central Services Building	Capitol Extension	School of Public Health	Medical School Building	Texas Department of Health	Sims Elementary School
Location - City		College Station	State College	Lubbock	Austin	Austin	Austin	Austin	Austin	Austin	Austin	Austin	Houston	Houston	Austin	Fort Worth
Location - State		TX	PA	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX
Number of buildings	#	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Year construction completed		1969	1990	1967	1880	1973	1961	1961	1960	1946	1980	1992	1975	1974	1958	1988
Year commissioning project completed		1997	1998	2001	1996	1993	1996	1996	1996	1995	1996	1996	1994	1994	1995	1994
Floor area served by commissioned systems	square feet	258,600	50,000	156,000	282,499	470,000	169,756	102,000	120,000	99,000	100,000	360,000	233,738	877,187	298,700	62,400
Building type(s)		Higher Ed/Lab/Office	Lab/Office	Higher Education/Lab/Office	Office	Office	Office	Office	Office	Office	Office	Office	Healthcare: Outpatient	Healthcare: Outpatient	Healthcare: Outpatient	Education: K 12
Number of deficiencies identified	#/building	26	26	27	1	8	6	6	4	5		8	3	1	2	1
Number of measures recommended	#/building	26	27	27	1	8	6	6	4	5		9	3	1	2	1
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-all	Yes-all	Yes-all		Yes-all	Yes-all	Yes-all	Yes-all	Yes-all		Yes-all	Yes-all	Yes-all	Yes-all	Yes-all
Commissioning cost	$/ft2 ($2003)		2.20	0.49	0.12	0.09	0.21	0.34	0.29	0.28	0.20	0.11	0.15	0.05	0.11	0.50
Direct commissioning cost as a fraction of total construction cost (new construction only)	%															
Total energy savings [weather-normalized]	kBTU/ft2-year		256.3	68.6						49.9						
Total energy savings [weather-normalized]	%		27.2%	18.6%						33.1%						
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)		2.30	0.30	0.35	0.08	0.34	0.16	0.09	0.52	0.09	0.32	0.32	1.18	0.04	0.27
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	0.22	3.34	0.77	0.83					0.65				2.03		
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years		1.0	1.8	0.3	0.9	0.5	1.6	2.4	0.5	1.9	0.3	0.4	0.0	2.1	1.4
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years		0.7	0.6	0.1					0.4				0.0		
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Data Source(s)		TAMU LoanStar file documents	Penn State CC Report (TAMU files); 2. Wei et al 2000; Giebler et al. 2000	Wei, G. Texas Tech CC Final Report, October 2001; TAMU LoanStar file documen	TAMU LoanStar file documents	Claridge et al 1994; Lui et al. 1994; Claridge et al 1996; TAMU LoanStar file	Claridge et al 1994; Claridge et al 1996; Gregerson 1997; Lui 1999; TAMU LoanStar	Claridge et al 1994; Claridge et al 1996; Gregerson 1997; TAMU LoanStar file	Claridge et al 1994; Claridge et al 1996; Gregerson 1997; Zhu et al. 1997; TAMU	Lui et al. 1996; Lui et al, 1999; Gregerson 1997; TAMU LoanStar file documents	TAMU LoanStar file documents	Gregerson 1997; Zhu et al. 1997; TAMU LoanStar file documents	Lui 1993; TAMU LoanStar file documents	Lui 1993; TAMU LoanStar file documents	TAMU LoanStar file documents	Lui 1993a; Claridge et al 1994; Claridge et al 1996; TAMU LoanStar file

APPENDIX E. Catalog of Projects (summary)

ID	Units	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider		TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)
Building name and location		Dunbar Middle School	Boiler Room	Basic Research	Old Clinic & Lutheran Pavillion	New Clinic	John Sealy North	Clinical Sciences	Basic Sciences	Moody Memorial	John Sealy South	Kleberg; Texas A&M University	Harrington Tower; Texas A&M University	Richardson Petroleum; Texas A&M University	Vet Med Center Addition-Research Tower; Texas A&M University	Blocker; Texas A&M University
Location - City		Fort Worth	Houston	Houston	Houston	Houston	Galveston	Galveston	Galveston	Galveston	Galveston	College Station	College Station	College Station	College Station	College Station
Location - State		TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX	TX
Number of buildings	#	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Year construction completed		1982	1954	1986	1970	1980	1978	1970	1971	1968	1978	1980	1970	1990	1990	1978
Year commissioning project completed		1993	1994	1994	1994	1995	1993	1995	1993	1994	1994	1996	1996	1996	1996	1997
Floor area served by commissioned systems	square feet	92,884	412,872	120,376	499,013	276,466	54,494	124,870	137,856	67,380	373,085	165,031	130,844	113,700	114,666	257,953
Building type(s)		Education: K 12	Healthcare: Outpatient	Healthcare: Outpatient	Healthcare: Outpatient	Healthcare: Outpatient	Healthcare: Inpatient	Higher Education/Lab	Higher Education/Lab/Office	Warehouse and Storage	Healthcare: inpatient	Higher Education/ Lab/Office	Office	Higher Education/Lab/Office	Higher Education/Office	Higher Education/Office
Number of deficiencies identified	#/building	1	3				3	3	2	3	4	23	5	11	3	14
Number of measures recommended	#/building	1	3				3	3	2	3	4	23	5	11	3	16
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-all	Yes-all				Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all
Commissioning cost	$/ft2 ($2003)	0.41	0.10	0.29	0.08	0.12	0.56	0.27	0.26	0.44	0.11	0.29	0.15	0.27	0.27	0.12
Direct commissioning cost as a fraction of total construction cost (new construction only)	%															
Total energy savings [weather-normalized]	kBTU/ft2-year											356.8	96.5	234.9	184.1	56.2
Total energy savings [weather-normalized]	%											49.5%	47.2%	50.1%	35.9%	30.1%
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.15	0.44	2.04	0.94	0.87	4.33	0.22	2.65	0.61	0.64	1.87	0.54	1.23	0.98	0.35
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)											3.23	1.00	2.13	1.74	0.70
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	2.0	0.2	0.1	0.1	0.1	0.1	1.0	0.1	0.6	0.1	0.1	0.2	0.2	0.2	0.3
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years											0.1	0.1	0.1	0.2	0.2
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Data Source(s)		Lui 1993a; Claridge et al 1994; Claridge et al 1996; TAMU LoanStar file	TAMU LoanStar file documents	Lui 1993b; TAMU LoanStar file documents	Lui 1993b; Lui 1993d; TAMU LoanStar file documents	Lui 1993b; Lui 1993e; TAMU LoanStar file documents	Lui 1993b; Lui 1993f; Claridge et al 1994; Claridge et al 1996	Lui 1993b; Lui 1993c; Claridge et al 1994; Claridge et al 1996; TAMU	Claridge et al 1994; Lui et al. 1994; Claridge et al 1996; Liu, TAMU LoanStar	Lui 1993b; Lui 1993f; Claridge et al 1994; Claridge et al 1996	Lui 1993b; Lui 1993c Claridge et al 1994; Claridge et al 1996	Turner et al. 2001; CC Report	Turner et al. 2001; TAMU LoanStar file documents	Turner et al. 2001; TAMU LoanStar file documents	Turner et al. 2001; TAMU LoanStar file documents	Turner et al. 2001; TAMU LoanStar file documents

APPENDIX E. Catalog of Projects (summary)

ID	Units	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider		TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)	TAMU/ESL College Station TX)
Building name and location		Eller O&M; Texas A&M University	Koldus; Texas A&M University	G.R. White Coliseum; Texas A&M University	Wehner; Texas A&M University				Chemistry North		Matheson Complex	Reed McDonald	Large Animal	Research Facility	Heep Center	Small Animal
Location - City		College Station	College Station	College Ststion	College Station	Lubbock	Lubbock	Lubbock	Lubbock	Lubbock	Salt Lake City	TAMU	TAMU	TAMU	TAMU	TAMU
Location - State		TX	TX	TX	TX	TX	TX	TX	TX	TX	UT	TX	TX	TX	TX	TX
Number of buildings	#	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Year construction completed		1973	1980	1960	1992	1966	1970	1970	1960	1968	1997					
Year commissioning project completed		1997	1997	1997	1996	2001	2001	2001	2001	2001	2002	1996	1996	1996	1996	1996
Floor area served by commissioned systems	square feet	180,316	110,272	177,838	192,001	205,000	118,000	129,000	48,000	48,000	370,000	77,435	140,865	114,666	158,979	150,000
Building type(s)		Higher Education/Lab/Office	Office	Public Order and Safety	Higher Education/Office	Higher Education/Office	Higher Education/Office	Higher Education/Office	Higher Education/Office	Higher Education/Office	Public Order and Safety	Higher Education	Lab	Higher Education	Higher Education	Lab
Number of deficiencies identified	#/building	16	14	5	10	56	15	18	15	17	23					
Number of measures recommended	#/building	16	14	5	10	58	15	18	15	17	23					
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all					
Commissioning cost	$/ft2 ($2003)	0.22	0.24	0.11	0.05	0.48	0.49	0.48	0.48	0.48		0.42	0.23	0.28	0.21	0.05
Direct commissioning cost as a fraction of total construction cost (new construction only)	%															
Total energy savings [weather-normalized]	kBTU/ft2-year	115.7	111.9	145.3	51.4	31.1	16.1	59.7	25.0	144.2	35.9					
Total energy savings [weather-normalized]	%	38.0%	36.5%	57.3%	23.9%	28.6%	11.4%	26.2%	7.3%	15.9%	28.7%					
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.69	0.62	0.77	0.28	0.19	0.04	0.29	0.07	0.49	0.21	0.58	1.81	1.42	0.46	0.19
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	1.36	1.15	1.36	0.50	0.43	0.14	0.68	0.22	1.51	0.44					
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	0.3	0.3	0.1	0.2	2.8	14.7	1.9	7.3	1.1		0.6	0.1	0.2	0.4	0.2
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	0.2	0.2	0.1	0.1	1.1	3.6	0.7	2.2	0.3						
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	C	C	C	C	C	C	C	C	C	C					
Data Source(s)		Turner et al. 2001; TAMU LoanStar file documents	Turner et al. 2001; TAMU LoanStar file documents	Turner et al. 2001; TAMU LoanStar file documents	Turner et al. 2001; TAMU LoanStar file documents	Wei, G. Texas Tech CC Final Report, October 2001	Wei, G. Texas Tech CC Final Report, October 2001	Wei, G. Texas Tech CC Final Report, October 2001	Wei, G. Texas Tech CC Final Report, October 2001	Wei, G. Texas Tech CC Final Report, October 2001	Turner et al. 2003; Zhu 2003	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997

APPENDIX E. Catalog of Projects (summary)

ID	Units	46	47	48	49	50	51	52	53	54	55	56	57	58	59
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider		PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)
Building name and location															
Location - City		Clearlake	Stockton	La Mesa	Sudbury	Hillsboro	Portland	Portland	Golden	Nashville	Portland	Seattle	Chattanooga	Portland	South Glenn
Location - State		CA	CA	CA	MA	OR	OR	OR	CO	TN	OR	WA	TN	OR	CO
Number of buildings	#	1	2	1	3	4	1	1	7	1	1	1	1	1	1
Year construction completed		1991	1986	1983	1960; 1968; 1985	1980; 1992; 1993; 1997	1970	1997		1985	1994	1933	1960	1978	1973
Year commissioning project completed		2001	2001	2002	1998	1999	2000	2004	2002	1996	2002	1998	1997	1996	1996
Floor area served by commissioned systems	square feet	30,244	45,372	125,000	230,400	805,000	261,000	489,700	275,200	250,000	185,500	233,500	175,000	224,000	120,000
Building type(s)		Lodging	Lodging	Office	Lab/Office	Office	Office	Office	Higher education/Retail/Office/Warehouse and Storage	Office	Lodging	Office	Office	Office	Retail
Number of deficiencies identified	#/building	9	9	8	6	2	30	21	5	18	23	15	38	19	22
Number of measures recommended	#/building	10	9	9	6	2	30	21	2	18	23	15	38	21	22
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-all	Yes-all	Yes-some		Yes-some	Yes-some	Yes-some	Yes-all	Yes-some	Yes-some	Yes-all	Yes-all	Yes-some	Yes-all
Commissioning cost	\$/ft2 (\$2003)	1.58	1.20	0.60	0.21	0.13	0.14	0.34	0.14	0.13	0.17	0.16	0.85	0.08	0.13
Direct commissioning cost as a fraction of total construction cost (new construction only)	%														
Total energy savings [weather-normalized]	kBTU/ft2-year	12.4	15.8	7.0	129.8	19.2	16.6	7.9	22.7		11.5			36.4	
Total energy savings [weather-normalized]	%	6.0%	9.6%	10.7%	38.2%	10.3%	17.6%	11.1%	6.0%		7.7%				
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	\$/ft2-year (\$2003)	0.33	0.30	0.18	0.49	0.13	0.03	0.16	0.14	0.17	0.14	0.06	0.38	0.06	0.13
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	\$/ft2-year (\$2003)	0.27	0.25	0.16	0.58	0.26	0.06	0.17	0.29		0.12				
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	4.6	3.9	3.3	0.4	0.9	4.5	1.4	1.2	0.6	1.3	2.5	1.8	1.6	0.8
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	5.8	4.7	3.7	0.4	0.5	3.2	2.0	0.5		1.4				
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E	E	D	E	E	E	E	E	E	E	E	E	A	D
Data Source(s)		PECI 2001a; Kahn et al. 2002	PECI 2001b; Kahn et al. 2002	PECI, 2002a	PECI and Boston Edison Co. 1998	PECI, 1999	PECI 1999; PECI 2000	PECI, 2003-2004 interim report and internal spreadsheets	PECI 2002b; PECI 2003	PECI 1996	PECI interim report (Jan 2002) and master findings spreadsheet (Dec 2002)	PECI internal files, 1997-1999	PECI 1997b	PECI 1996b	PECI 1996c

APPENDIX E. Catalog of Projects (summary)

ID	Units	60	61	62	63	64	65	66	67	68	69	70	71	72
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider		PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	Facility Dynamics (Baltimore, MD)	Quantum Energy Services and Technologies, Inc. - QuEST (Oakland, CA)	Quantum Energy Services and Technologies, Inc. - QuEST (Oakland, CA)	Quantum Energy Services and Technologies, Inc. - QuEST (Oakland, CA)	Quantum Energy Services and Technologies, Inc. - QuEST (Oakland, CA)	Nexant (San Francisco, CA)	Quantum Energy Services and Technologies, Inc. - QuEST (Oakland, CA)			
Building name and location												Office1	Office2	Lab1
Location - City		Auburn	Phoenix	Nampa	Oakland	Oakland	Oakland	Oakland	Oakland	Oakland	Oakland	Rancho Cordova	Sacramento	Sacramento
Location - State		MA	AZ	ID	CA	CA	CA	CA	CA	CA	CA	CA	CA	CA
Number of buildings	#	1	1	1	1	18	2	2	12	1	2	1	1	1
Year construction completed		1992	1986		1999		1911	1993		1980	1939/1985		1984	1997
Year commissioning project completed		1996	1996	2003								2000	2000	2000
Floor area served by commissioned systems	square feet	106,684	80,000	23,210	1,014,133	371,343	317,000	750,000	226,383	210,406	467,685	150,000	383,200	94,000
Building type(s)		Retail	Office	Public Assembly	Office	Higher Education	Service/Office	Lodging/Public Assembly	Higher Education	Public Order and Safety	Office	Office	Office	Lab/Office
Number of deficiencies identified	#/building	20	14	18	13	1	7	7	1	13	7	11	8	8
Number of measures recommended	#/building	20	14	16	5	1	4	8	1	15	8	11	8	8
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-some	Yes-some	Yes-all								Yes-some	Yes-some	Yes-some
Commissioning cost	$/ft2 ($2003)	0.16	0.25	2.03	0.08	0.30	0.22	0.09	0.27	0.24	0.17	0.20	0.12	0.41
Direct commissioning cost as a fraction of total construction cost (new construction only)	%													
Total energy savings [weather-normalized]	kBTU/ft2-year			36.2	2.6	15.3	5.0	8.1	22.4	9.3	6.5	5.4	15.7	33.2
Total energy savings [weather-normalized]	%			29.5%	4.6%	5.0%	1.9%	2.3%	15.8%	2.0%	1.5%	4.5%	21.2%	28.6%
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.09	0.23	0.44	0.07	0.32	0.08	0.11	0.36	0.40	0.20	0.11	0.24	0.64
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)			0.63	0.05	0.21	0.06	0.09	0.25	0.21	0.11	0.12	0.26	0.76
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	1.6	0.9	4.6	1.3	0.9	2.6	0.9	0.8	0.6	0.9	1.8	0.5	0.6
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years			3.2	1.8	1.5	3.4	1.0	1.1	1.1	1.5	1.6	0.5	0.5
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	D	E	D	E	E	E	E	E	E	E	C	C	C
Data Source(s)		PECI 1996d	PECI 1996e	PECI and Sawtooth Technical Services 2003	Quantum Energy Services and Technologies project files	Quantum Energy Services and Technologies project files	Quantum Energy Services and Technologies project files	Quantum Energy Services and Technologies project files	Quantum Energy Services and Technologies project files	Quantum Energy Services and Technologies project files	Quantum Energy Services and Technologies project files	Bourassa et al. 2004	Bourassa et al. 2004	Bourassa et al. 2004

APPENDIX E. Catalog of Projects (summary)

ID	Units	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider								Herzog/Wheeler	Sieben Energy	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	PECI (Portland, OR)	
Building name and location		Hospital1	Office3	Office4	Office5	Office6	Office H: Port of Portland Building, 700 N.E. Multnomah	High-Tech Research Facility	203 N. LaSalle St.			Nordstrom				Nampa City Hall
Location - City		Sacramento	Sacramento	Sacramento	Sacramento	Sacramento	Portland									Nampia
Location - State		CA	CA	CA	CA	CA	OR		IL	CA	CA	CA	CA	CA	CA	ID
Number of buildings	#	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Year construction completed		1996	1991	1990	1995	1965										1982
Year commissioning project completed							1993	1984	1995	1994	1994	1994	1994	1994	1994	2003
Floor area served by commissioned systems	square feet	300,000	400,000	324,000	352,000	308,360	312,000	44,000	623,000	146,000	152,000	170,000	48,000	50,000	120,000	23,000
Building type(s)		Healthcare: Inpatient and Outpatient/Lab	Office	Office	Office	Food Service/Office	Office	Lab	Office	Retail	Service	Retail	Office	Office	Office	Office
Number of deficiencies identified	#/building	19	5	9	9	10	7		640			21				19
Number of measures recommended	#/building	19	5	9	9	10	7									
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-some	Yes-some	Yes-some	Yes-some	Yes-some	Yes-all									
Commissioning cost	$/ft2 ($2003)	0.13	0.06	0.11	0.09	0.10	0.13	0.64	0.18	0.42	0.43	0.45	0.51	0.64	0.20	2.43
Direct commissioning cost as a fraction of total construction cost (new construction only)	%															
Total energy savings [weather-normalized]	kBTU/ft2-year	(14.9)	3.8	4.0	6.0	5.5										45.8
Total energy savings [weather-normalized]	%	-7.4%	5.1%	7.1%	12.0%	7.7%										
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	(0.09)	0.08	0.09	0.13	0.16	0.03	2.15	0.28	0.18	0.09	0.29	0.40	0.26	0.04	0.73
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	(0.13)	0.09	0.09	0.14	0.15	0.04									0.79
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	(1.5)	0.8	1.2	0.7	0.6	3.7	0.2	0.5	1.9	3.7	1.2	1.0	2.0	4.6	3.4
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	(1.0)	0.7	1.2	0.6	0.6	2.8		-							2.4
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	C	C	C	C	C	E		E	E	E	E	E	E	E	E
Data Source(s)		Bourassa et al. 2004	Bourassa et al. 2004	Bourassa et al. 2004	Bourassa et al. 2004	Bourassa et al. 2004	Piette et al. 1995; Piette and Nordman 1996	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997	Gregerson 1997	SBW and Skumatz 2003

APPENDIX E. Catalog of Projects (summary)

ID	Units	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
Existing building or new construction		existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing	existing
Commissioning provider			Facility Improvement Corporation (Great Falls, MT)		KeithlyWelsh	Systems West Engineers (Eugene, OR)	Northwest Engineering Service, Inc.		TAMU/ESL College Station TX)	TAMU/ESL College Station TX)						
Building name and location		Army Aviation Support Facility	East Valley Middle School	University of Montana - Gallagher Hall	Beaverton School District - Sexton Mountain Elementary School	DAS Public Services Building	Portland State University - Science Building	Clover Park Elementary School	Acute-care hospital	In-patient mental health	Middle school	Elementary school	Elementary School (unit ventilators)			
Location - City		Helena	Helena	Missoula	Beaverton	Salem	Portland	Lakewood	Minneapolis							
Location - State		MT	MT	MT	OR	OR	OR	WA	MN	MN	MN	MN	MN	MN	WA	WA
Number of buildings	#	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1
Year construction completed		1999	1999	1997		1955			1982	1962	1959		1965			
Year commissioning project completed		2001	2002	2002	1999	2000	2000	2002	1999	1998	2000	1999	2001	2001	1993	1993
Floor area served by commissioned systems	square feet	56,000	64,000	110,380	65,000	172,400	213,000	95,405	600,000	37,300	220,000	105,625	93,900	59,000	95,000	11,232
Building type(s)		Retail	Education: K 12	Higher Education	Education: K-12	Office	Higher Education	Education: K-12	Healthcare: Inpatient	Healthcare: Inpatient	Education: K 12	Education: K 12	Education: K-12	Office	Office	Retail
Number of deficiencies identified	#/building	112	103	249	37	22	55	19	14	14	481	131	30	6		
Number of measures recommended	#/building								15	23	481	167	31	6		
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown								Yes-some							
Commissioning cost	$/ft2 ($2003)	0.35	0.44	0.31	0.41	0.42	0.11	1.00	0.41	1.33		0.30		0.85	0.03	0.57
Direct commissioning cost as a fraction of total construction cost (new construction only)	%															
Total energy savings [weather-normalized]	kBTU/ft2-year	57.1	3.7	15.6	10.9	0.3	3.0	5.4	34.1	131.6				17.0		3.0
Total energy savings [weather-normalized]	%								13.5%							10.0%
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.61	0.04	0.22	0.20	0.04	0.04	0.08	0.33	1.33				0.20		0.02
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	0.61	0.03	0.23	0.21	0.03	0.03	0.08	0.40	1.63				0.31		
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	0.5	12.2	1.4	1.8	10.0	2.7	12.9	1.2	0.9				4.2		20.7
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	0.3	10.4	0.5	-	7.5	-	6.8	1.0	0.8				0.1		8.4
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E	E	E	E	E	E	E	D	A				E	E	E
Data Source(s)		SBW and Skumatz 2003	SBW and Skumatz 2003	SBW and Skumatz 2003	SBW and Skumatz 2003; Tso et al (no date); NEEA (no date-a)	SBW and Skumatz 2003; Tso et al (no date).	SBW and Skumatz 2003; Tso et al (no date); NEEA (no date)	SBW and Skumatz 2003	MNCEE 2001a	MNCEE 2001b	MNCEE 2001c	MNCEE 2001d	MNCEE 2001e	MNCEE 2001f	Stum et al 1994	Stum et al 1994

APPENDIX E. Catalog of Projects (summary)

ID	Units	103	104	105	106	
Existing building or new construction		existing	existing	existing	existing	
Commissioning provider				HEC (ESCO)	HEC (ESCO)	
Building name and location				Capital High School	Special Care Facility	
Location - City				Charleston	Charleston	
Location - State		WA	WA	WV	WV	
Number of buildings	#	1	1	1	1	
Year construction completed				1988	1986	
Year commissioning project completed		1993	1993	1993	1989	
Floor area served by commissioned systems	square feet	5,690	32,800	253,000	123,500	
Building type(s)		Office	Office	Education: K-12	Healthcare: Inpatient	
Number of deficiencies identified	#/building					
Number of measures recommended	#/building					
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown					
Commissioning cost	$/ft2 ($2003)	0.83	0.11	0.70	3.86	
Direct commissioning cost as a fraction of total construction cost (new construction only)	%					
Total energy savings [weather-normalized]	kBTU/ft2-year		1.2			
Total energy savings [weather-normalized]	%		31.0%			
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)		0.01	0.30	0.89	
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)					
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years		9.8	1.8	3.0	
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years		4.0			
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E	E	E	E	
Data Source(s)		Stum et al 1994	Stum et al 1994	Zachwieja and Williams 1994	Zachwieja and Williams 1994	

APPENDIX E. Catalog of Projects (summary) NEW CONSTRUCTION

ID	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Existing building or new construction		new	new	new	new	new	new	new	new	new	new	new	new	new	new
Commissioning provider		PECI	PECI	PECI	PECI	Affiliated Engineers, Inc	Affiliated Engineers, Inc								
Building name and location						Alameda County Med. Ctr. Highland Hospital Campus New Critical Care and Chiller Building	UCSF Mission Bay Building 24B - 500 16th Street	Office A: Utah Power & Light Mt. Ogden Service Center	Office B	Office C: City of Portland Water Control Center and Water Quality Laboratory, N. Interstate Ave.	Office D: Regency Building, 2749 E. Parley's Way	Office E: Towers Building, 10600 S. Towne	Office F: Utah Human Services Building	Office G: Metro Service District Headquarters	Theater I: Cannes Cinema Center, 1026 12th Ave.
Location - City		Vancouver	Gresham	Portland		Oakland	San Francisco	Ogden		Portland	Salt Lake City	South Jordan	Salt Lake City		Seaside
Location - State		WA	OR	OR	TN	CA	CA	UT		OR	UT	UT	UT		OR
Number of buildings	#	1	1	1	1	2	1	1	1	1	1	1	1	1	1
Year construction completed		1997	2001	1998	2001	2003	2002	1992	1993	1993	1993	1993	1993	1993	1993
Year commissioning project completed		1997	2002	1998	2002	2003	2002	1994	1994	1994	1993	1994	1994	1994	1993
Floor area served by commissioned systems	square feet	84,000	180,000	87,000	20,000	324,000	450,000	19,860	21,776	24,842	34,800	66,000	66,473	84,060	12,500
Building type(s)		Healthcare: Outpatient	Office/Service/Warehouse & Storage	Healthcare: Inpatient & Outpatient	Lab	Healthcare: Inpatient & Outpatient/Lab/Office	Lab/Office/Public Assembly/Warehouse & Storage	Office	Office	Laboratory	Office	Office	Office	Office	Public Assembly
Number of deficiencies identified	#/building	112	30	33	202	128	705	4	3	3	15	7	8	13	3
Number of measures recommended	#/building	112	30	33	57	128	705	4	3	3	15	7	8	13	3
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-all	Yes-all	Yes-all	Yes-all			Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all
Commissioning cost	$/ft2 ($2003)	0.50	0.59	0.16	4.77	2.13	1.22	0.11	0.49	0.24	0.67	0.11	0.10	0.26	0.33
Direct commissioning cost as a fraction of total construction cost (new construction only)	%	0.3%	0.4%	0.1%	2.1%	0.6%	0.3%	0.1%	0.3%	0.2%	0.4%	0.1%	0.1%	0.2%	0.2%
Total energy savings [weather-normalized]	kBTU/ft2-year							0.1	3.7	2.2	5.0	1.5	1.6	11.8	1.8
Total energy savings [weather-normalized]	%														
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)							0.00	0.10	0.02	0.06	0.03	0.03	0.17	0.03
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)							0.00	0.09	0.03	0.06	0.04	0.05	0.26	0.04
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years							24.6	4.1	10.6	8.8	3.6	2.3	1.3	10.0
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years							31.5	5.4	7.8	10.4	2.9	2.0	1.0	7.7
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E		C				E	E	E	E	E	E	E	E
Data Source(s)		Project binder issues logs and project budget information.	PECI 2002	PECI - Kaiser Interstate Medical South Commissioning Final Report	PECI and The McCarty Company 2002	Affiliated Engineers, Inc., project files	Affiliated Engineers, Inc., project files	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996

APPENDIX E. Catalog of Projects (summary)

ID	Units	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Existing building or new construction		new	new	new	new	new	new	new	new	new	new	new	new	new	new	new
Commissioning provider																
Building name and location		Retail J: Pine Crest Fabrics, 9707 N.E. Colfax	Retail K: Jack Tedsen Medical Strip Mall, Washington Blvd.	Grocery L: Food Value Grocery Store #8, 1121 N.W. Newport Ave.	Hospital M: Columbia Memorial Hospital Building	Motel N: Best Western Rama Inn	Grocery O: United Grocers Price-Less Foods Store	Hotel P: Governor Hotel, 10th Ave. and Alder St.	Mental Hospital	University Classroom	University Classroom	University Lab/Classroom		University Lab/Classroom	University Lab/Classroom	
Location - City		Portland	Crescent City	Bend	Astoria	Redmond	Roseburg	Portland								
Location - State		OR	CA	OR	OR	OR	OR	OR	MT	MT	MT	MT	MT	MT	MT	MT
Number of buildings	#	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1
Year construction completed		1993	1993	1993	1993	1993	1993	1993	1996	1996	1996	1996	1996	1996	1996	1996
Year commissioning project completed		1993	1993	1993	1994	1993	1993	1993	1996	1997	1997	1997	1997	1999	1999	1998
Floor area served by commissioned systems	square feet	14,879	17,050	19,400	22,954	29,371	38,500	64,500	63,526	1,072	110,380	110,303	32,268	44,966	140,700	4,523
Building type(s)		Warehouse and Storage	Healthcare: Outpatient	Food Sales	Healthcare: Inpatient	Lodging	Food Sales	Lodging	Healthcare: Inpatient		Higher Education	Food Sales/Lodging	Office	Lab	Lab	Office
Number of deficiencies identified	#/building	2	2	7		4	10	2								
Number of measures recommended	#/building	2	2	7		4	10	2								
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all	Yes-all								
Commissioning cost	$/ft2 ($2003)	0.20	0.62	0.52	0.26	0.95	0.28	0.25	0.42	18.20	0.81	1.02	0.62	1.79	1.55	2.08
Direct commissioning cost as a fraction of total construction cost (new construction only)	%	0.1%	0.4%	0.3%	0.2%	0.6%	0.2%	0.2%	0.3%		0.6%	0.7%	3.4%	1.1%	2.3%	1.4%
Total energy savings [weather-normalized]	kBTU/ft2-year	0.4		14.9		0.7	8.7	0.1								
Total energy savings [weather-normalized]	%															
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.01		0.25		0.01	0.16	0.00								
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	0.01		0.35		0.02	0.25	0.00								
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	19.4		1.6		62.9	1.4	136.1								
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	20.5		1.5		59.4	1.1	105.0								
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E		E	E	E	E	E								
Data Source(s)		Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Piette et al. 1995; Piette and Nordman 1996	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000

APPENDIX E. Catalog of Projects (summary)

ID	Units	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
Existing building or new construction		new	new	new	new	new	new	new	new	new	new	new	new	new	new	new
Commissioning provider																
Building name and location		Lab/Classroom Addition	Juvinile Detention	Mental Hospital		Prison	Prison	Prison	Prison			Student Union Building	Physics/ Astronomy Building	Project B	Project C	Project D
Location - City													Seattle	Seattle	Seattle	Seattle
Location - State		MT	MT	MT	MT	MO	MO	MO	MO	MO	WA	WA	WA	WA	WA	WA
Number of buildings	#	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Year construction completed		1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1994	1994	1994	1994
Year commissioning project completed		1999	1999	1999	2001	1998	2001	2001	2001	2000	2001	2001	1994	1994	1994	1994
Floor area served by commissioned systems	square feet	72,165	45,915	79,130	202,648	245,000	381,000	380,891	685,000	76,000	51,000	30,000	256,000	108,000	233,000	207,000
Building type(s)		Lab	Public Order and Safety	Healthcare: Inpatient	Public Assembly	Public Order and Safety	Public Order and Safety	Public Order and Safety	Public Order and Safety	Lab	Healthcare: Inpatient	Higher Education	Higher Education/Lab/Office	Higher Education/ Lab/Office	Higher Education/Lab/Office	Higher Education/Lab/Office
Number of deficiencies identified	#/building															
Number of measures recommended	#/building															
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown															
Commissioning cost	$/ft2 ($2003)	0.93	1.27	1.66	0.57	1.62	1.36	1.09	1.27	3.82	1.32	1.00	0.86	3.19	1.43	4.14
Direct commissioning cost as a fraction of total construction cost (new construction only)	%	0.8%	0.7%	1.0%	0.8%	0.5%	0.8%	0.6%	0.7%	1.3%	0.9%	1.0%	0.4%	0.8%	0.8%	1.8%
Total energy savings [weather-normalized]	kBTU/ft2-year												26.2			
Total energy savings [weather-normalized]	%															
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)												0.09			
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)												0.24			
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years												7.5			
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years												3.6			
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E												E			
Data Source(s)		Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Wilkinson 2000	Caner 1996; 1997	Caner 1997	Caner 1997	Caner 1997

APPENDIX E. Catalog of Projects (summary)

ID	Units	45	46	47	48	49	50	51	52
Existing building or new construction		new	new	new	new	new	new	new	new
Commissioning provider		Farnsworth Group	Farnsworth Group	Farnsworth Group	Farnsworth Group	Farnsworth Group	Farnsworth Group	CH2M Hill (Portland OR)	
Building name and location		Supermarket	Science Center		Vivarium	Science Building	Elementary School	Ada County Courthouse	Boise State University Recreation Center
Location - City								Boise	Boise
Location - State		WI	CO	CO	NC	AL	IN	ID	ID
Number of buildings	#	1	1	1	1	1	1	1	1
Year construction completed		1999						2001	2002
Year commissioning project completed		2000						2001	2002
Floor area served by commissioned systems	square feet	14,350	84,427	365,850	196,996	344,743	77,391	340,000	90,148
Building type(s)		Food Sales	Public Assembly	Healthcare: Inpatient	Lab	Lab	Education: K 12	Public Order and Safety	Public Assembly
Number of deficiencies identified	#/building	4						97	183
Number of measures recommended	#/building	7							
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown								
Commissioning cost	$/ft2 ($2003)	2.04	2.13	0.88	1.78	1.18	0.48	0.75	0.82
Direct commissioning cost as a fraction of total construction cost (new construction only)	%	1.4%	1.4%	0.6%	1.2%	0.8%	0.3%	0.5%	0.5%
Total energy savings [weather-normalized]	kBTU/ft2-year							4.2	7.8
Total energy savings [weather-normalized]	%								
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)							0.08	0.13
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)							0.08	0.13
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	-	-	-	-	-	-	9.7	6.5
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years		-	-	-	-	-	4.6	2.4
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E							E	E
Data Source(s)		Altweis and McIntosh 2001; Altweis 2002	Dorgan et al 2002	Dorgan et al 2002	Dorgan et al 2002	Dorgan et al 2002	Dorgan et al 2002	SBW and Skumatz 2003	SBW and Skumatz 2003

ID	Units	53	54	55	56	57	58	59
Existing building or new construction		new	new	new	new	new	new	new
Commissioning provider		Western Montana Engineering		Environmental and Engineering Services, Inc.				Keithly/Welsch Associates Inc (Burien WA)
Building name and location		Wallace Building - State Prison	Beaverton Library	Courthouse Square Transit Facility	Lane Community College - Day Care Center	North Clackamas High School	Salem-Keizer School District - Marion F. Miller Elementary School	Bainbridge Island School District - B.I. High School
Location - City		Deer Lodge	Beaverton	Salem	Eugene	Clackamas	Salem	Bainbridge Island
Location - State		MT	OR	OR	OR	OR	OR	WA
Number of buildings	#	1	1	1	4	1	1	1
Year construction completed		2002		2001	2000	2000		2000
Year commissioning project completed		2003	2000	2001	2000	2000	2000	2000
Floor area served by commissioned systems	square feet	23,300	69,500	160,000	18,300	250,000	49,000	144,000
Building type(s)		Public Order and Safety	Public Assembly	Public Assembly	Education: K-12	Education: K-12	Education: K-12	Education: K-12
Number of deficiencies identified	#/building	71	57	101	6	75	74	148
Number of measures recommended	#/building							
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown							
Commissioning cost	$/ft2 ($2003)	1.43	1.73	0.49	0.92	0.52	1.15	0.39
Direct commissioning cost as a fraction of total construction cost (new construction only)	%	1.1%	1.2%	0.3%	0.6%	0.4%	0.8%	0.3%
Total energy savings [weather-normalized]	kBTU/ft2-year	4.8	2.9	7.9	1.9	2.9	(0.6)	9.3
Total energy savings [weather-normalized]	%							
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.05	0.01	0.11	0.04	0.03	0.03	0.19
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	0.05	(0.00)	0.12	0.04	0.03	0.04	0.21
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	29.0	303.1	4.2	21.3	15.0	33.7	1.8
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	22.2		1.2	16.5	16.7	37.8	0.9
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E	E	E	E	E	E	E
Data Source(s)		SBW and Skumatz 2003	SBW and Skumatz 2003; Tso et al (no date).	SBW and Skumatz 2003; Tso et al (no date); NEEA (no date-e)	SBW and Skumatz 2003; Tso et al (no date).	SBW and Skumatz 2003; Tso et al (no date).	SBW and Skumatz 2003; Tso et al (no date).	SBW and Skumatz 2003; NEEA (no date-c)

APPENDIX E. Catalog of Projects (summary)

ID	Units	60	61	62	63	64	65	66	67	68	69
Existing building or new construction		new	new	new	new	new	new	new	new	new	new
Commissioning provider					Test Comm LLC (Spokanne, WA)		HEC (ESCO)	HEC (ESCO)			
Building name and location		Cheney Cowles Museum	DOC - Women's Correctional Center	Othello Community Hospital	Spokanne Community College - Health Sciences Building	Processing and Environmental Technology Laboratory (PETL)	Women and Children's Hospital Addition	CAMC Memorial Surgery Replaceme nt Addition			Industrial (electronics tech.)
Location - City		Spokane	Gig Harbor	Othello	Spokane	Albuquerque					
Location - State		WA	WA	WA	WA	NM	WV	WV	WA	WA	WA
Number of buildings	#	1	1	1	1	1	1	1	1	1	1
Year construction completed		2002	2001	2000	2003	2000	1988	1994			
Year commissioning project completed		2002	2001	2000	2003	2003	1993	1994	1993	1993	1993
Floor area served by commissioned systems	square feet	78,000	58,000	51,000	60,000	151,000	43,000	122,000	42,000	32,000	60,000
Building type(s)		Public Assembly	Public Order and Safety	Healthcare: Inpatient	Higher Education	Lab	Healthcare: Inpatient	Healthcare: Inpatient	Education: K-12	Office	Other
Number of deficiencies identified	#/building	45	26	39	43						
Number of measures recommended	#/building										
Verification of Measure Installation	Yes-all; Yes-some; No; Unknown										
Commissioning cost	$/ft2 ($2003)	1.52	1.71	1.80	1.66	7.46	9.08	5.42	0.15	0.11	1.01
Direct commissioning cost as a fraction of total construction cost (new construction only)	%	0.7%	1.1%	1.2%	1.4%	3.9%	5.9%	1.9%			
Total energy savings [weather-normalized]	kBTU/ft2-year	18.1	2.4	21.2	3.4				0.8	0.6	19.2
Total energy savings [weather-normalized]	%										
Inflation-corrected energy savings, local energy prices, excluding non-energy impacts	$/ft2-year ($2003)	0.21	0.02	0.29	0.05	2.03	3.84	1.23	0.01	0.00	0.14
Inflation-corrected savings, using standardized US energy prices, including non-energy impacts if quantified	$/ft2-year ($2003)	0.21	0.02	0.30	0.05						
Payback time - [no normalizations] nominal values: raw nominal-price data (mixed dollars and prices), excluding non-energy impacts	Years	7.0	77.1	5.6	36.0	3.3	1.9	3.6	19.6	18.1	5.6
Payback time - Standardardized energy prices and inflation-corrected commissioning costs, including non-energy impacts	Years	6.0	74.7	4.8	25.8	-			7.9	7.3	2.3
Energy savings determination [select answers that correspond to the energy data given in prior rows. See Appendix D for definitions]	A; B; C; D; or E	E	E	E	E	E	E	E	E	E	E
Data Source(s)		SBW and Skumatz 2003	SBW and Skumatz 2003	SBW and Skumatz 2003	SBW and Skumatz 2003	Savage (no date)	Zachwieja and Williams 1994	Zachwieja and Williams 1994	Stum et al 1994	Stum et al 1994	Stum et al 1994